LECTURES

ON

ELECTRICAL MEASUREMENTS.

FLEEMING JENKIN.

LECTURE I.

ON

ELECTRICAL MEASUREMENTS,

DELIVERED BY

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WRITTEN BY

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THE object of the lectures, which I shall have the honor to deliver to you, is not to give simply a set of practical rules concerning special problems which may come before you every day, but rather to explain a series of rules and principles, by which you may be enabled to calculate the dimensions and conditions required to produce given results, and by which you may be able to record all electrical observations, which you may have to make, in an intelligible form; a form, not intelligible to yourselves only, but to all others who are familiar with the same system of measurement, in whatever parts of the world they may live.

Now the meaning of a measurement is essentially that it shall be a comparison; whatever has to be measured must be compared with something else, generally of the same kind; we compare a length with some standard of length, or a weight with some standard of weight, and this standard, in each case, is called a unit, a unit of each particular thing to be measured; and as we have units of length and units of weight, so it is necessary that, in order to make electrical measurements, we should have electrical units.

Definition of Electrical Measurements.

The electrical magnitudes which can be measured, (or in other words, those phenomena which are capable of being compared so accurately one with another, that their comparisons may be called measurements), are Electrical Resistance, Electrical Currents, Electrical Quantity, Electrical Capacity, and Electromotive Force:—here are

five distinct magnitudes or things which can be compared, each one with others of the same kind, all of which have certain mathematical relations one with another; and each of these different magnitudes requires a distinct unit in which it is to be measured.

Units of Measurement, Force.

Is it a matter of complete indifference what unit you employ to measure any particular magnitude? Of course it is necessary that the unit or measure, in each case, should be of convenient dimensions, of convenient size, but independently of that I think I shall be able to show you, that it is not a matter of indifference what particular size you use for your unit. As regards the fundamental units in mechanics, time, space, and mass, I think they might have been chosen almost at hazard, of any convenient magnitude; there seems to be no particular reason why one mass more than another, or why one space or one time more than another should be chosen; but all these things have already been established, so that I need hardly trouble you with them. The only doubt in settling upon a new system of electrical measurement would seem to be, whether we should adopt the English or the French system, but whichever of these two be adopted, the relations between the fundamental units and the electrical magnitudes, of which I am about to treat, are the same. In England we have the standard yard, as the unit of length, though feet are more commonly used in practice, the second of mean solar time as the unit of time, and the mass of the grain avoirdupois as the unit of mass: in France there is the metre, supposed to represent a fraction of the earth's circumference, the same unit of time (the second), and the gramme as the unit of weight. Now, these, as I have already said, may be chosen arbitrarily, but there are other kinds of units which cannot be so chosen: for instance when we come to the unit of force, we find that there are certain definite relations between force and time, space and mass, so that we may define the unit of force—as that force which will produce a unit of speed, by acting upon a unit of mass, during a unit of time; a force which, acting for a second upon a grain, will give a velocity of one foot per second is the English measure of the unit of force, and the same relation, of course, holds good in French measures.

Unit of Work.

The unit of work, in the same way, is not independent; it was at one time thought that it might be chosen at hazard, and the power of a horse was taken as the unit of work; in so doing, people were only following a perfectly sound analogy, they compared one kind of work with another, as they compared one length with another length:—but, mark what has happened, we now never think of horses in speaking of horse-power, we think of the foot-pound as the common unit of work, so that here a unit, chosen arbitrarily, has had to fall back upon a derived unit. Thus it is not sufficient, in choosing new units, to select a unit of the same kind as the thing to be measured, it is necessary first to consider whether there be not some philosophical relation between the new unit to be selected, and the units of time, space, and mass. Now the unit of weight, a grain, is an imperfect one, because the grain is a quantity or magnitude that varies in different parts of the world,

for that reason we base our unit of force on the unit of mass rather than the unit of weight. The common unit of force, with which you are in the habit of dealing, is always a weight, and when anyone thinks of a force he thinks of a weight, and that the force is equal to so many pounds or kilogrammes; but owing to the peculiarity that the force exerted by a particular weight is not the same in all parts of the world, it is preferable to take the unit of force, as I have already defined it, and the unit of work as equal to this new absolute unit of force acting through the unit of space, rather than the foot-grain or foot-pound, which are in more common use.

Now we have built upon the fundamental units of time, space and mass, certain other definite units which are mechanical, resting however upon these three fundamental measurements:—in exactly the same way, it is quite possible to build up all the Electrical units upon the same fundamental units of time, space and mass, and on consideration you will perceive that it must so be done. The only way in which we know anything of these electrical agents is by the mechanical phenomena which they produce: we see that certain *forces* are acting, for instance a Magnet may be deflected, in one case, from the position in which it would naturally stand, this pre-supposes a *force* to deflect it and we observe, not the current, but the *force*. Again two electrified balls attract one another and we know that they are electrified simply by observing the *force* with which they attract each other; and the more we analyze the electrical phenomena which come before us, the more clearly we shall see that all we know about them are simply their mechanical effects and, *a priori*, you might expect to be able to measure them in mechanical units.

Electrical Quantity.

I must now explain accurately what I mean by each of the terms I shall employ.—First, with regard to electrical quantity:—Electricity is not a thing which can be seen or felt, one does not perceive it by any particular sense, but what is meant by a quantity of electricity may be described as follows:—when two electrical conducting bodies are connected with the same pole of a voltaic battery they repel one another, this may be observed in a manner sensible to the eye by the employment of a very large battery; the two poles of a battery produce equal and opposite effects, and if the same bodies were connected with the opposite poles of a battery, they would attract one another. When in a condition to exert this force, whether of repulsion or attraction, they are said to be charged with a quantity of electricity. It must be understood that these are merely names or definitions given to a certain condition of matter. Now the force with which one electrified body acts upon another varies under various conditions, but the quantity with which a given small body is charged, may be taken as proportional to the force with which it acts, through the air, upon another equal quantity, at a unit distance; if the quantities be not equal, the force exerted between them is proportional to the product of the quantities and this force is also inversely proportional to the square of the distance between the electrified bodies. If two bodies,

each charged with a given quantity of electricity, be incorporated they will be found to be charged with the sum of the two quantities, and it is this which justifies the use of the word *quantity*, the term being expressive of something which can be added together.

ELECTROSTATIC MEASURE.

1st.	$f = \frac{q \cdot q_1}{d^2}$	f = *force*.
2nd.	$c = \frac{q}{t}$	q = *quantity*.
		t = *time*.
3rd.	$e = \frac{w}{c.t}$	e = *electromotive force*.
		r = *resistance*.
4th.	$r = \frac{e}{c}$	c = *current*.
		w = *work*.
5th.	$w = c.^2 r.t$	

Now in the table headed Electrostatic measure the first equation, $\left(f = \frac{q \cdot q_1}{d^2}\right)$, expresses the relation above desoribed, this equation virtually defines the unit of electrical quantity, for if we suppose $q = q_1$ we have $q^2 = f. d^2$, and q will therefore be equal to *one*, when f and d are both equal to *one*, in other words the unit of quantity must be that quantity, which will repel another equal quantity, at a unit distance, with the unit of force; thus we get our first mechanical unit of electricity, derived from the fundamental units, in a manner precisely analogous to that in which mechanical units of force or work are derived from the fundamental units. Quantities, thus defined, may be multiplied as ordinary algebraic magnitudes and, when one is positive and the other negative, the product, and therefore the force f, will be negative, that is to say the attraction will be changed into repulsion; if two electrical quantities are combined together, the resulting quantity will be the simple algebraic sum of the parts. Thus the phenomena which result from experiment, justify the use of the word quantity and the use of the very simple formula above mentioned.

I am not now explaining how these measurements are made, but simply defining what is meant by the word quantity of electricity and by the term derived unit of Electricity. We need not conceive electricity as a separate thing at all, but as it is convenient to speak of the velocity of sound, so we may speak of the quantity of electricity, without for a moment imagining that Electricity has an independent existence, or is anything but a condition of matter or force exerted.

Electrical Current.

We now pass on to the meaning of the words Electrical Current. When two electrified balls have been charged by the opposite poles of a battery, with equal and opposite quantities of electricity, and are joined together by a conductor, a piece of copper wire for instance, they lose in a short time their electrical properties and become neutral; but, during the first moment of their connection, the wire which joined them acquired very definite and altogether distinct properties, and we say that, when a wire possesses these properties, an electrical current is flowing through it. The analogy of language is obvious, for if we suppose water from a basin flowing down through a pipe into another basin, we have a fair analogy with the current of electricity, our basins representing the balls, charged with a positive and negative quantity of electricity, and the connecting pipe being in the place of the conducting wire joining them.

Now this connecting wire, while engaged in neutralizing equal and opposite quantities of electricity, exerts a force upon any magnet, or upon any wire similarly circumstanced, in its immediate neighbourhood; if certain bodies, called electrolytes, are used to replace the wire over a part of its length, these bodies will be decomposed; and what we mean by an Electric Current is this, that the wire or body through which this current is flowing, possesses all the properties just enumerated. Now if we actually join two large balls with a piece of wire, after they have been electrified, we produce a sensible current, but it will be of short duration, and probably a current of this kind would never have been observed at all, if we had had no other means of exciting a current; we can, however, produce very nearly permanent effects, by continually charging the two balls and discharging them through the wire, thus producing a succession of very short currents, succeeding one another very rapidly; and if, instead of charging these two balls with the battery and then letting them discharge themselves through the wire, we simply join the two extremities or poles of the battery, so as to complete the circuit, then the properties, which the wire or conductor thus gets, are similar to those given by the rapid succession of short discharges, but the current becomes permanent, instead of being intermittent.

The obvious definition of the strength of a current,—I employ the word strength in preference to the term intensity, because the latter has been used in a loose vague way,—is that it shall be proportional to the quantity of electricity conveyed in one second of time, and then, knowing how to measure quantity, we are able to measure currents in terms of that quantity; thus when we say that one current is double another, we mean that it conveys twice as much electricity through a given wire, in a second of time, as the other current does; and when we say, convey a quantity, we mean that it shall be able to neutralize twice the quantity of electricity that the first current could neutralize. This condition is expressed in the second equation in the table of Electrostatic measure, viz.: $c = \frac{q}{t}$, which shows that the current is

equal to the total quantity conveyed, divided by the time which the current has lasted. If we find the total quantity of electricity neutralized in a given time, through a given wire connecting two Leyden jars or two electrified balls, and divide that total quantity by the time, we have the measure of the mean current in absolute measure. It follows that the definition of the unit of current is naturally that current which conveys the unit of quantity in the unit of time.

We have now a second derived electrical unit, not chosen arbitrarily, but derived, by mathematical relations, from the fundamental units of time, space, and mass.

Electro-motive Force.

We have hitherto spoken simply of the current as produced by joining two electrified balls or by a battery, and of the statical effects which a quantity or a current of electricity was able to produce; but it is found that a current of electricity, as I have defined it, cannot exist without doing work of some kind or its equivalent: for example, it heats a conductor through which it passes, or it raises a weight, by forming an electro-magnet, or it magnetizes a piece of soft iron, or effects chemical decomposition, in fact in some way it does work, or that which is equivalent to work; it is well known that, when a body is heated, the amount of such heat is capable of being expressed in terms of work or energy; the mechanical equivalent of heat has been measured with considerable accuracy, thus one unit of heat is said to be equal to 772 foot-grains in British measure, or 4157 absolute units of work, in metres, seconds, and grammes; when a current heats a wire, it is doing what is equivalent to a certain amount of work, and by measuring the heat, the amount of current required to accomplish a certain amount of work may be ascertained. This does not mean that a current is always employed in raising weights, but that it cannot exist without producing some of the effects mentioned, which are all mensurable in terms of work. Now, work done, pre-supposes a force in action, and the immediate force which produces the current, in the transfer of a certain amount of electricity, is called the "Electromotive Force." What is meant by the Electromotive force of a battery is the force which produces the current, and, in producing the current, does the work. We naturally attribute the power to that part of the circuit where the consumption of materials takes place; thus just as we speak of the boiler as the source of power in a steam engine, so we speak of the battery as the source of power in a voltaic circuit, because there the consumption of zinc goes on. Now just as a battery may produce a current, so the difference of electrical condition between two balls is also able to produce a current; the force producing this current, between two electrically charged balls, is as much an electromotive force as that exerted by the poles of a battery, the mechanical fact, that they are able to produce a current and to do work, shows that they have an electromotive force acting between them, and the force which produces the current and does work, by means of that current, is the "Electromotive Force," in whatever way produced, acting under the same laws, and measurable in the same way.

Difference of Potential.

The difference of condition between two charged balls or two poles of a battery, in virtue of which they can do work by the agency of a current, is often called a difference of potential, and generally the words electromotive force and difference of potential are interchangeable, and the electromotive force, or proximate cause of the work, is defined as proportional to the amount of work done between two points, when a given quantity of electricity is transferred from one to the other; the same quantity of electricity, driven by the same electromotive force, invariably does the same work; and when with equal quantities of electricity, transferred in a given time, the amount of work done in one case is double that in another, the electromotive force in the first case is said to be double that in the second. This may be made clearer by analogy: a quantity of electricity may be supposed similar to a quantity of water. The electromotive force may be conceived as similar to the head or pressure, which forces water through a pipe and does work, in consequence of a difference of head. In hydraulics we must take into account the velocity with which the water enters a pipe as well as the velocity with which it leaves it, and for this reason it is not accurate in all cases to speak of "the difference of level," we therefore prefer the term "head" as representing the force which drives the water through the pipe. Now the electromotive force which drives the current through a conductor, may be conceived as precisely analagous to this head of water. If you have equal currents passing through two pipes, equal quantities of water pass in equal times; but if the difference of head in the one case is double that in the other, the total fall in the first case is double that in the second, and we have twice the amount of work done in the same time, by the same amount of water falling through twice the height. Now if the work done in one case, by a given quantity of electricity, is double that done in another, we must infer that the electromotive force is twice as great, just as we infer that the fall of water in the one case must be double that in the other, and we might actually measure that fall by the work done. This relation between work and current, is expressed in equation No. 3, viz., $e = \frac{w}{c.t}$ a relation which is simply mathematical, and it follows that the unit of electromotive force exists between two points, when that force will do a unit of work in a unit of time, for every unit of current which it causes to pass between the two points in the same time, or more simply for every unit quantity of electricity of which it causes the transfer, whether that transfer be slow or quick. We thus build up a somewhat complicated, but still strictly mathematical system, from these three fundamental measurements.

Electrical Resistance

We now come to the last of the four chief properties of electrical force which are capable of being measured, viz.: "Electrical Resistance." It has been found by experience that when the electromotive force remains constant, so that the work done by the transfer of a given quantity of electricity remains constant, the transfer of electricity

may be made to take place in very different times or, in other words, currents of different magnitudes may be produced, and very different amounts of work done in a given time, by modifying the material and form of the conductor through which the current circulates.

Some substances offer but a small opposition to the passage of a current, while others, on the contrary, interpose a very considerable impediment to its passage. The property, in virtue of which any substance offers this opposition, is called its "Electrical Resistance." It is easily understood that when a force is acting, tending to do work, unless it meets with some definite resistance, it will expend itself in an infinitely short space of time, at an indefinitely rapid rate. The only reason why a battery, for instance, does not explode, so to speak, and produce all its heat in a second of time is that the wire or other conductor, through which the action must take place, offers a certain Resistance, and it is this quality of restricting the amount of work done, or the amount of current in circulation with a given electromotive force, which is called "Electrical Resistance," and it is defined naturally as proportional to the current passing in a given circuit, when a given electromotive force is maintained between its two extremities. The relation expressed in the 4th equation, known as Ohm's law, viz.: $r = \frac{e}{c}$, implies the above definition of Electrical Resistance. It follows that the unit of electrical resistance, will allow a unit current to flow under the action of a unit electromotive force.

Measurement of Electrical Resistance.

The measurement of Resistance is sufficiently simple, if by measurement is meant the mere comparison of one resistance with another; if the practical unit of resistance, selected as the standard, with which all other resistances are to be compared, has once for all been so constructed as to correspond with the above definition, then all measurements, made by comparison with the standard unit of Electrical Resistance, will really be expressed, not in terms of an arbitrary standard, but in terms of the fundamental units of time, mass, and space. Thus I have shown how the four magnitudes, quantity, current, electromotive force, and resistance, can all be expressed in terms of units, involving no hypothesis as to the nature of electricity, connected one with another by simple mathematical laws, and involving, for their practical determination, the measurement of the mechanical units of time, space, and mass only.

Work done by current in overcoming Resistance.

Electrical Resistance is not exactly analogous to mechanical resistance, but more accurately corresponds to a co-efficient of resistance. In order to make it analogous to the case of water forced through a pipe, it would be necessary to suppose that the resistance offered by the pipe or by the machine set in motion by the current of water, increased exactly in proportion to that current: in electricity, the mechanical resistance appears to increase exactly in proportion to the current, so that the total amount of work done is equal to the square of the current multiplied by the resistance, see equation No. 5 in table of Electrostatic measure, $w = c^2\, r.\, t$, where t represents the unit of time.

In this equation we may perhaps regard $c.r$ as expressing, what I term, the mechanical resistance; and c the quantity of electricity forced past that resistance.

From the above it is evident that, if we wish to follow the natural mathematical relations between the quantities involved in the above equations, we are not free to choose the units of Current, Resistance, Electromotive force, &c., at hazard for ourselves; were we to do so, we should get all kinds of useless and inconvenient coefficients into our calculations. The units, as I have defined them, which we have thus obtained are deductions from the natural mathematical relations between the things to be measured, and in using these units in any calculations which we may have to make, we shall introduce no useless coefficients. An exactly analogous case is that of cubic measure: if we measure a solid, in terms of cubic feet, we can pass to square or lineal measure without any useless coefficients. If, on the contrary we measure in gallons and then pass to acres or feet, it gives much more trouble: the French system, where the cubic and square measures are derived, according to simple mathematical relations, from the lineal measure, is most convenient in this respect. The practical use of this series of units, chosen as I have described, is evident, for had the units not been chosen according to the true mathematical series thus formed, the coefficients introduced would enter into all the more complex expressions involved in a very perplexing manner.

Electro-magnetic Measure.

We must not, however, assume that the above is the only possible series of equations from which units might be derived, using the fundamental units of time, mass, and space; it may be quite possible, and in fact in very many cases it may be more convenient, to start from other mechanical phenomena than those hitherto described; for instance, one fundamental relation between our units might be found by the force known to be exerted by a current of electricity upon a magnet, or by one current of electricity upon its neighbour: a series of units, starting from this basis, instead of from the observation of the force exerted between two statically charged balls, (but otherwise connected one with another by exactly the relations hitherto described), might be built up, this is called the Electro-magnetic series and the equations thus obtained are shown in the following table.

Electro-magnetic Measure.

1st $G = \dfrac{A.C \times A_1.C_1}{D^3}$

or $G = m.l.\ C.\ 2\ \pi.\ n.\ k.\ \dfrac{1}{k^2}\ \text{Cos.}\ \theta.$

2nd. $C = \dfrac{Q}{t}$

3rd. $E = \dfrac{W}{C.t}$

4th. $R = \dfrac{E}{C}$

5th. $W = C^2.R.t.$

G = moment, tending to turn magnet.
m = strength of pole of magnet.
l = distance between poles.
$m\ l$ = moment of magnet.
C = strength of current.
k = radius of coil.
n = number of turns in coil.
θ = angle between axis of magnet and plane of coil.
A = area of small circuits.
D = distance between small circuits or magnets.

I have explained the Electro-static system first, as it is more simple. The object of the electro-magnetic series is to take into account the force G, with which a current acts upon a magnet; this introduces a fifth equation between G and four unknown quantities q, c, r, and e. If I am to avoid all coefficients, I must cease to regard one of the five equations as fundamental; to do this I give up the first equation, $\left(f = \frac{q.q_1}{d^2}\right)$, of the Electro-static series, it being that which may be most conveniently changed, and I substitute for it the first equation of the Electro-magnetic series,

$$\left(G = \frac{A.C \times A_1.C_1}{D^3} \text{ or } m.l.C. \times 2\pi.n.k.\frac{1}{k^2} \times Cos\ \theta.\right)$$

which latter expresses the relation between the force, which is exerted by a current upon a magnet or by one current upon another. The idea which it expresses is simply that the unit length, say 1 foot of wire bent into a circle round a magnet, and having a unit current passing through it, will exert a unit force upon a unit pole of a magnet, placed in its centre. Take several yards of wire and bend it round in several circles: now the unit of electric current will be passing through that coil when every foot of it exerts the unit force upon the unit pole of a magnet placed in its centre. If we could obtain a unit pole of a magnet and could place it in the centre of the coils of a tangent galvanometer, the force exerted on that pole, would be inversely proportional to the square of the distance of the current from the pole, or to the square of the radius of our circular coil k, and directly proportional to the length of the circuit in the coil $= 2\,\pi.\,n.\,k$, and to the strength of the current C. This strength, defined as above, would be simply equal to the force observed multiplied into k^2 and divided by the length of the coil $2\,\pi.\,n.\,k$. We cannot, however, get an isolated pole of a magnet, though it is easy to define the unit pole of a magnet, because the poles act upon each other very simply: the force with which they act on each other is equal to the product between the two poles m and m_1, divided by the square of the distance D, or $f = \frac{m.m_1}{D^2}$, so that two unit poles act with unit force at a unit of distance: since we cannot obtain one pole of a magnet we must use, as in the tangent galvanometer, a short magnet with its poles joined together at a certain distance. The same definition of

the strength of current then leads to a more complex expression for the value of G, the moment tending to turn the magnet, *vide* equation 1. This moment will be unity if $m, l, C, k,$ and $2\ \pi, n, k$ are each equal to unity and if $\theta = o$. Substituting, therefore, this more complicated equation, for the 1st of the Electro-static series, all the others may be retained, and we get a completely new series of measures, accurately and mathematically deduced, one from the other, and bearing a simple and constant ratio, one to the other: this is called the Electro-magnetic system of units of absolute measure.

We might arrive at the same definition of the unit current, without using magnets either for observation or in our definitions.

Ampère's Theory.

Ampère has shown that the action of a small closed circuit, at a distance, is the same as that of a small magnet, provided the axis of the magnet be placed normal to the plane of the circuit, and the moment of the magnet be equal to the product of the current, into the area of the circuit which it traverses.

Thus, let two small circuits, having areas A and A_1, be placed at a great distance D from each other, in such a way that their planes are at right angles to each other, and that the line D is in the intersection of the planes. Now, let currents C and C_1 circulate in these conductors; a force will act between them, tending to make their planes parallel, and the direction of the currents opposite. The moment of this couple will be

$$G = \frac{A.C \times A_1.C_1}{D^3}$$

Hence the unit electric current, conducted round two circuits of unit area in vertical planes, at right angles to each other, one circuit being at a great distance, D, vertically above the other, will cause a couple to act between the circuits of a magnitude $\frac{1}{D^3}$. The definition of the unit current, (identical with the unit founded on the relations given above), might be founded on this action quite independently of the idea of magnetism.

Time will not, however, admit of explaining this more fully. My object has been, to-night, simply to show that just as cubic measure is naturally expressed in a certain set of units derived from length, so all the Electrical phenomena, of which I shall have to speak in the course of the other lectures, which I hope to give on this subject, may be measured in units, which are mathematically derived from the fundamental units of time, space, and mass, and not only that this may be done, but that it ought to be done.

Practical Measurement of Electrical Resistance.

The practical mode in which Electrical measurements are made is comparatively simple: for example, as regards resistance, resistance coils, representing units and multiples of units, are arranged in boxes for the purpose of comparison; the coils are simply lengths of wire, adjusted so as to offer resistances of from one to ten thousand times the standard or unit of resistance; the coils are further so arranged

that they can be readily combined in any desired series, so that with, say, 16 coils, any desired resistance, from 1 to 10,000, can be instantly obtained. If the standard coil, from which these sets are made, has been adjusted so as to be equal to the unit of Resistance defined, as has been explained, and determined by special experiment once for all, the practical operation, which we have to carry out, is simply to compare any wire or other conductor, the resistance of which is to be determined, with the set of coils of which the Resistance is known.

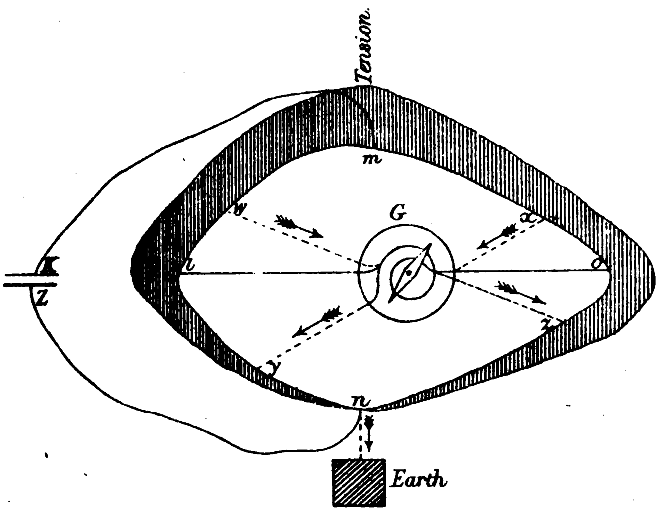
Thus, however complex and difficult the original experiment may be, by which the standard unit is fixed, the only practical operation, subsequently required, is a simple comparison between two magnitudes of the same kind. Thus, in France cubic or liquid measure is directly derived from lineal measure and, though the buyers or sellers of liquids do not measure them by the metre, the person who determined the standard measure for liquids, did refer directly to the unit of length, and therefore it is, that the French measure of capacity, the cubic metre, measured in vessels properly adapted for the purpose, is a much more scientific measure than the gallon, and a much more definite and convenient one to use, as all Engineers will readily admit; so, in practical measurements of resistance and other electrical magnitudes, it is unnecessary to refer on each occasion of comparison to the fundamental units, because that reference has been made once for all, by those who prepare the standards in each case, while the practical operator knows nothing, and need know nothing, of the process by which his unit or comparison was determined.

In the three lectures which I shall deliver, following this one, in the present course, I shall allude principally to the measurements of currents, quantity, electromotive force and of capacity, the meaning of which word I have not yet explained. I shall say very little of the practical measurement of Resistance, because this process is so much better understood than the measurement of the other electrical magnitudes. At one time, a conductor was simply described as a piece of silver or platinum wire of so many inches or feet or yards long and of such a diameter; now we find everywhere, that the resistance of a conductor is defined as equal to so many units: some originally chose one unit and some another, some adopted arbitrary measures, such as a mile, a yard, or a metre of any given metallic conductor, but we have gradually come to adopt these mathematical units, and all measurements of resistance are now referred to the standard unit of the British Association.

Wheatstone's Bridge.

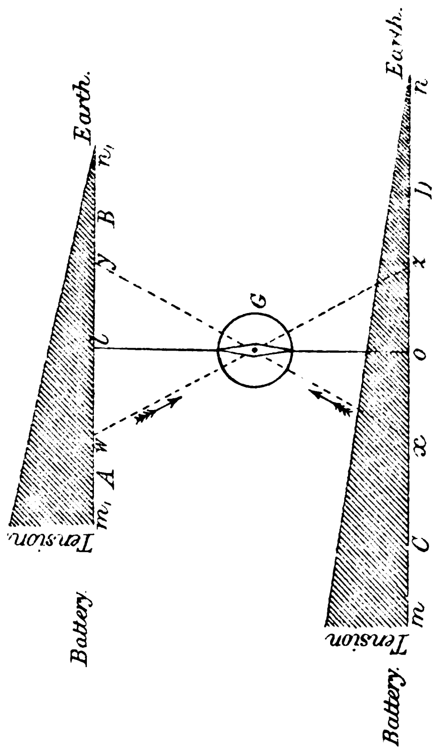
I will explain one of the different methods of comparing electrical resistances. Let us suppose that we have got our standard unit, representing, in the shape of a certain length of wire, the electro-magnetic unit, as above defined. We may compare any other conductor with that standard by means of Wheatstone's Bridge or Balance, as it is sometimes called. This contrivance consists in the arrangement of four conductors, as shown in sketch Fig. 1, with a battery and galvanometer.

Fig. 1.



Now when you join the two points *m* and *n*, by the conductors *m l n* and *m o n*, and the points *l* and *o*, by the conductor *l*, *o*, the latter having in circuit a galvometer *G*, and when the points *m* and *n* are connected with the positive and negative poles of a battery, if no current whatever is observed to pass through the galvanometer *G*, a very simple ratio must exist between the four conductors, viz.: that the Resistance of *m l* : that of *n l* : : the resistance *m o* : that of *n o* : suppose then the two wires *m l* and *n l* are two equal standards, by simple trial a fourth wire *n o* can be adjusted equal to any third given resistance *m o*, which we wish to repeat. Thus we can compare or construct multiples of any known unit of resistance, but more than this, when we have these multiples, so arranged that we can at pleasure vary the ratio of *m l* and *n l* as required, we can then determine the ratio of any unknown resistance *n o*, to any known resistance *m o* by

Fig. 2.



simply varying the ratio of *m l* to *n l*, until no current is observed to pass through the galvanometer: a simple proportion exists between the four resistances, so that when three are known, we determine or measure the fourth, by a simple rule of three sum. The action of this contrivance will be understood from the following explanation: if one end of a wire *C D* be connected at *m* to the positive pole of a battery, and the other to the earth at *n*, (see Fig. 2), the negative pole of the

same battery being also connected to earth, we have the whole electromotive force of the battery exerted at the point m, and this electromotive force decreases with perfect regularity, from the battery to the earth, the electromotive force, or tension at any point, being simply proportional to the resistance which remains between the point and the earth; thus, half way along the wire we have half the electromotive force or tension, as it is sometimes called, at three quarters of the distance along the wire, we have one fourth of the tension and so on. If the wire is not of uniform resistance, the proposition is true if, for the word wire, the word resistance be substituted. Again, if we connect another wire, as $A\ B$, opposing a less resistance to the current, with the same poles of the same battery, we have at m and m_1 the same tension in both wires, and the tension in $A\ B$ gradually diminishing, as before, to zero at n and n_1. Now if we join the two parts of these wires, at the points where they are in a perfectly similar condition as to tension, as from l to o, by a metallic conductor, having in circuit a galvanometer G, there is no difference of tension and no electromotive force whatever between these points, l and o, and the galvanometer will not indicate any current, passing from one to the other. Now in order that this condition may be fulfilled, it is only necessary to subdivide the two wires in the proportion already defined, viz.: that $m_1\ l : n_1\ l :: m\ o : o\ n$. If the cross wire were arranged as shown by the dotted line $w\ z$, the tension at the point w being greater than that at z, a current would flow from w to z, as shown by the arrow, and would deflect the galvanometer to one side, say to the right.

If the cross wire, on the other hand, connected the two points x and y, the tension at x being greatest, a current would flow through the cross wire, in the opposite direction, and would also deflect the galvanometer, in the opposite direction, or say to the left.

Thus, by a tentative process, we can determine what points of any two conductors, arranged in this way, we can join, so that no current shall pass between them, and thus we obtain points at which the tension is equal in the two conductors, and these points subdivide the conductors according to the simple proportion described, giving us the means of calculating the resistance of any one of the subdivisions in terms of the three others. Suppose the straight wires of Fig. 2 bent round, so that the parts bearing the same letters are brought in contact, and you will obtain Fig. 1, so that the demonstration, obtained by the aid of Fig. 2, applies to the arrangement sketched in Fig. 1. The hachures are, in both figures, intended to indicate the tension which, at any given point, is supposed proportional to the width of those hachures; the two figures correspond, and are intended to represent the same thing, under different forms; they explain, in a very simple manner, the general principles of Wheatstone's Electrical Balance; the reason why no current passes through the galvanometer, when the proper proportion between the four branches obtains, is very apparent when we once perceive that the tensions at the two points joined must, in that case, be equal. To prove the same proposition by reference to currents only, without taking

into consideration this difference of electromotive force produced by their passage along the wire, is a more complicated process.

Resistances. Specific

The following tables give the specific resistances of several metals, that is to say, the resistance of one foot of each metal weighing one grain:

TABLE I.

Specific resistance, in B.A. units, of metals and alloys, at 0° Centigrade, from Dr. Matthiessen's experiments.

Names of Metals.	Resistance of a wire one foot long, weighing one grain.	Resistance of a wire one metre long, weighing 1 gramme.	Resistance of a wire one foot long, 1-1000 inch in diam	Resistance of a wire one metre long, one millimetre in diam.	Approximate per centage of variation in resistance, per degree of temperature at 20°
Silver annealed	0·2214	0·1544	9·936	0·01937	0·377
„ hard drawn .	0·2421	0·1689	9·151	0·02103	..
Copper annealed ..	0·2064	0·1440	9·718	0·02057	0·388
„ hard drawn.	0·2106	0·1469	9·940	0·02104	..
Gold annealed	0·5849	0·4080	12·52	0·02650	0·365
„ hard drawn ...	0·5950	0·4150	12·74	0·02697	..
Aluminium anneald	0·06822	0·05759	17·72	0·03751	..
Zinc pressed	0·5710	0·3983	32·22	0·07244	0·365
Platinum annealed.	3·536	2·464	55·09	0·1166	...
Iron annealed	1·2425	0·7522	59·40	0·1251	...
Nickel annealed ...	1·0785	0·8666	75·78	0·1604	...
Tin pressed	1·317	0·9184	80·36	0·1701	0·365
Lead pressed	3·236	2·257	119·39	0·2527	0·387
Antimony pressed...	3·324	2·3295	216·0	0·4571	0·389
Bismuth pressed ...	5·054	3·525	798·0	1·689	0·354
Mercury liquid	18·740	13·071	600·0	1·270	0·072
Platinum Silver, alloy hard or annealed.........	4·243	2·959	143·35	0·3140	0·031
German Silver, hard or anneal.	2·652	1·850	127·32	0·2695	0·044
Gold Silver alloy, hard or anneal.	2·391	1·668	66·10	0·1399	0·065

TABLE II.

Constants, for metals or alloys, by which to calculate the resistance R, at temperature t, from the resistance r at zero :—$R = r\,(1 + a.\,t \pm b.\,t^2)$.

	a.		*b.*
Pure Metals	0·003824	+	0 00000126
Mercury	0·0007485	—	0·000000398
German silver	0·0004433	+	0·000000152
Platinum silver	0·00031	...	...
Gold silver	0·0006999	—	0·000000062

TABLE III.

Resistance, in B A units, of Wires one foot long, weighing one grain.

Temperature Centigrade.	Soft Copper.	Hard Copper.	German Silver.	Platinum Silver.
0	0·2064	0·2106	2·652	4·24
5	0 2102	0·2147	2·657	4·25
10	0·2144	0·2188	2·661	4·25
11	0·2153	0·2197	....	....
12	0·2161	0 2205	....	....
13	0·2170	0·2214	....	....
14	0·2178	0·2222	....	....
15	0·2186	0 2231	2 666	4·26
16	0·2194	0·2239	....	....
17	0·2203	0·2248	....	....
18	0·2211	0·2256	....	....
19	0·2220	0·2265	....	....
20	0·2228	0·2272	2·670	4·27
21	0·2237	0·2283	....	....
22	0·2242	0·2288	....	....
23	0·2253	0·2299	....	....
24	0·2262	0·2308	....	....
25	0·2271	0·2317	2·675	4·27
26	0·2279	0·2325	....	....
27	0·2287	0·2334	....	....
28	0·2296	0·2343	....	....
29	0·2305	0·2362	....	....
30	0·2313	0·2360	2·680	4·28
31	0·2322	0·2369	....	....
32	0·2328	0·2375	....	....
33	0·2340	0·2388	....	....
34	0·2348	0·2396	....	....
35	0·2357	0·2405	2·684	4 28
36	0·2365	0·2413	....	....
37	0·2376	0·2424	....	....
38	0·2383	0·2432	....	....
39	0·2391	0·2440	....	....
40	0·2400	0·2449	2·689	4·29

From these tables the resistance of any wire, of known weight per foot, can be directly calculated.

Not only can the conducting power of so-called conductors be measured, but the insulating power of the so-called insulators can be equally well expressed, in terms of resistance. Insulators and conductors both conduct and both resist; but a body is called an insulator when it has a very high specific resistance, and a conductor when it has a low specific resistance. The only practical difference, between the measurement of the resistance of an insulator and that of a conductor, is that, in the latter case, the simple B. A. unit, often called an "Ohm," is used, while in the former, a multiple, or one million Ohms, often called a "megohm" is employed; precisely as, for length, a foot or an inch

is used for small measurements and a mile for large distances. The specific resistance of insulators is often defined differently from that of metals, being taken as the resistance of a cube foot of the material supposed to be joined to the opposite poles of the battery, through two metal plates, pressed against the opposite faces of the cube. The object of the change of definition being, to diminish the enormous array of figures required to express the vast resistance of a long thread of insulating material, and also to facilitate practical calculations ; for while conductors are generally used in the form of wires, insulators more frequently occur under conditions, in which it is easier to calculate the resistance sought from that of a cubic foot, than from that of a wire, weighing one grain per foot.

LECTURE II.

ON

ELECTRICAL MEASUREMENTS,

DELIVERED BY

FLEEMING JENKIN, ESQ., F.R.S.,

At the Royal Engineer Establishment, Chatham, on the 21*st February*, 1867.

WRITTEN BY

CAPTAIN R. H. STOTHERD, R.E.,

AND CORRECTED BY THE LECTURER.

I propose to night to treat solely of the measurement of currents of electricity.

Laws of Currents.

You are probably familiar with the simplest laws of these currents :— you know for instance, that a current of electrity is equally strong in all parts of a simple circuit, and that currents, which have equal effects on a magnet, are equal, though this last truth is not unfrequently forgotten. People speak of an intensity current and a quantity current as if, though they might exert equal forces on a given magnet, they were nevertheless not equal, or were possessed of some other peculiar property than simple strength or magnitude. The fact is that one and the same current may be produced by two very different arrangements. An example, drawn from the flow of water, will illustrate my meaning ; we may have the same quantity of water flowing through two different pipes, one of them a short and the other a long pipe, while the same current would be sent through the short pipe by a small head of water, as would be sent through the long pipe by a very large head of water. Now if we change the resistance to the passage of these currents, by adding an equal length of pipe in each case, you perceive that we may almost stop the current passing through one pipe, but hardly interfere with the passage of the water, flowing through the other. We may have added equal resistances but, as the resistances were not equal in the first instance, we will have produced very different effects upon the

currents of water. Even so we may have equal currents of electricity, conveyed through a short and a long wire, the first due to a comparatively small, and the last due to a comparatively large electromotive force: that passing through the short wire is sometimes called a quantity current, and that through the long wire an intensity current. Though this language is not strictly correct it is convenient to retain the words, using them in the sense just defined. The fact is that the quantity of electricity conveyed may in both cases be the same; the quantity of electricity conveyed being the same, though conveyed along very different circuits, *i.e.* circuits of which the resistance differs greatly. The currents themselves are equal, where they exert equal forces on the same magnet, passing, of course, at the same distance from it, or, in other words, through the coils of the same galvanometer.

Comparison of Currents.

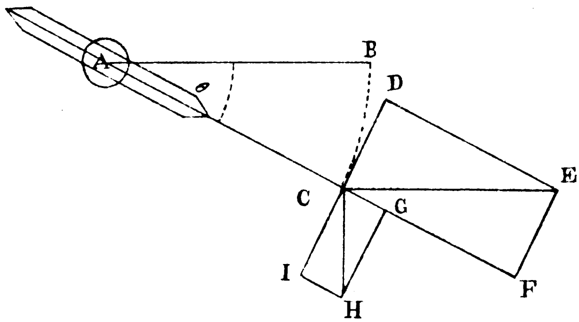
The simplest comparison that can be made between two currents, is obtained precisely in this way, by the deflection due to the force they exert on a given magnet. You pass first one current through the coils of an ordinary detector, and then the other; if a current produces a considerable deflection, it is a comparatively strong current; if it produces a small deflection, it is a comparatively weak current, and the angle of deflection produced affords a comparison, though of course a rough one, of the strength of each current; but this test, correct though it be in principle, is frequently misapplied. When a current is passing through any given circuit, we must not insert a detector and then suppose that we are measuring the original current by the detector, for we have really modified that original current, by introducing an additional resistance into the circuit; and, if the resistance of the detector happens to be much greater than that of the original circuit itself, we shall have reduced the strength of the current very considerably. The coil of a detector is a long insulated wire of considerable resistance, and we cannot, therefore, accurately determine the current in any particular circuit, unless we take into consideration the resistance of the detector, which we introduce for the purpose of observation. Now a detector, though it indicates the presence of a current, and will, with more or less accuracy, show whether a current passing through it is comparatively strong or weak, cannot, in the proper sense of the term, be said to measure a current, inasmuch as the relative strengths of the currents do not bear any known proportion to the deflections they produce in a detector. We may, by observing the amount of deflection, conclude that one current is stronger than another: we should, however, be in error, if we supposed that a current, producing a deflection of 40°, was only twice as strong as one giving a deflection of 20°. In most detectors, it would require three or four times the current to double the deflection.

Tangent Galvanometer

In order to obtain an instrument by which measurements, or correct comparisions can be made, we must use a deflecting coil of some accurately known form, such that the law, according to which the current will exert its force upon the magnet, can be calculated. Knowing that law, we shall be able, by an easy and accurate calculation, to deter-

mine, from the deflections observed, the ratio of the several currents producing these deflections. Such an instrument we have in the tangent galvanometer. From the deflections observed on this instrument, we obtain data as to the strengths of the various currents we pass through it, and these data are given in a convenient form for calculation. The simplest tangent galvanometer consists of large circular coils of wire, with a comparatively short magnet, freely suspended, in their centre. Suppose A B, Fig. 3, to represent in plan the line in which the magnet would lie, if not deflected by the current; let the coil be placed in a vertical plane, containing this line A B. Let the magnet now be deflected from its natural position by a current, to the direction A C, forming an angle θ with the line A B; when the magnet is very short, so that its poles do not very sensibly leave the centre of the

FIG. 3.



circular coil of wire, of which the instrument is composed, the force tending to deflect the pole of the magnet remains constant, and may be represented by a line C H, perpendicular to the magnetic meridian, and also perpendicular to the plane of the coils of the instrument. Now, if this force be resolved into its components, in the directions C G and C I, only one of these, viz. C I, tends to turn the magnet further in that direction, the other, C G, being balanced by the similar component, in the opposite direction, acting on the other pole. Again, let C E parallel to A B, represent the horizontal force of terrestrial magnetism, acting on one pole, and suppose it resolved into its two components, C F and C D; C F is balanced by the similar and opposite component, acting on the other pole. The remaining component C D, when the force of the current is such as to balance the needle at the angle θ with the magnetic meri-

dian, must be equal to C I. Hence we have C I $=$ C H. Cos θ and C D $=$ C I $=$ C E. Sin θ,

therefore C H. Cos θ $=$ CE. Sin θ : and C H $= \frac{\text{Sin } \theta}{\text{Cos } \theta} \times$ C E

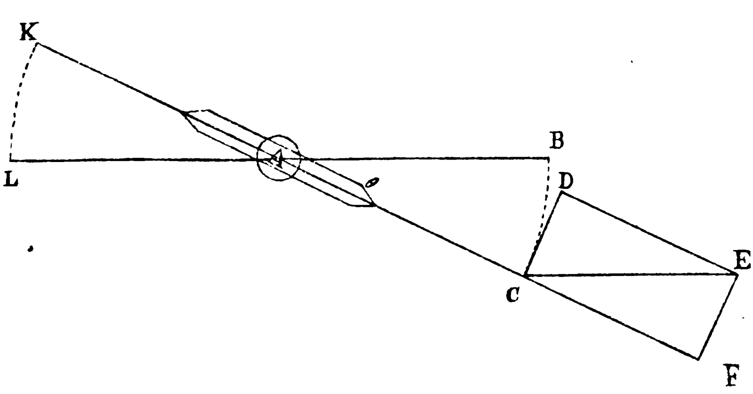
$= \tan \theta \times$ C E.

Consequently, forces produced by electrical currents on each pole of the magnet are proportional to the tangents of the angle of deflection, multiplied into the number expressing the horizontal component of the earth's magnetism ; but, the earth's magnetism being constant during the limited period required for any set of observations, the currents are truly proportional to the tangents of the angles observed.

Sine Galvanometer The sine galvanometer is a second instrument, by which accurate comparisons of currents can be made. The form and arrangement of the coils and magnet may be the same as for the tangent galvanometer, but the coils, instead of being fixed, are moved round the vertical axis of supension of the magnet, following that magnet, until magnet and coils take up a new position in one plane, when the deflecting force of the current in the coils is balanced by the component of the earth's magnetism. The coils need not be circular, and may be as close as possible to the magnet. The magnet itself may be made longer as, the coils being moved round with it, its greater length will not cause its poles to be moved out of the plane of those coils when a current is passing through them, while it will increase the leverage, and consequent directive effect, of terrestrial magnetism.

Let A B, (Fig. 4), as before, represent the direction in plan of the undeflected magnet and let C E represent the force exerted by the earth's magnetism in a horizontal plane on one pole, then resolving C E into its components, C D and C F, we have one of these, viz., C F, balanced by the corresponding component acting on the opposite

FIG. 4.



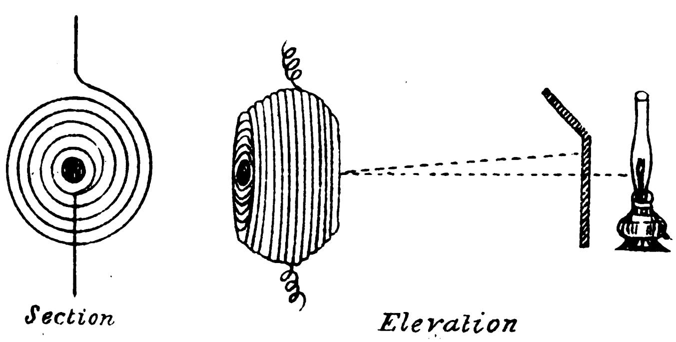
pole of the magnet, as in the former case. Now, in the sine galvanometer, the coil being itself moved round with, and kept in the same plane as, the magnet, the force, exerted by the current tending to turn it still further, always acts in a direction perpendicular to the plane of the coil and to the magnetic axis of the magnet and, at the particular point where the force of terrestrial magnetism is exactly balanced, the force exerted by the current will be exactly equal and opposite to the component, C D, of the force of terrestrial magnetism. Now C D=C E. Sin. θ, the instrument, therefore, measures the strength of currents, which vary as the sine of the angle of deflection, multiplied into the force exerted by terrestrial magnetism, which, for the reasons already stated, may be neglected in comparing deflections obtained in one place and at one time. The currents are thus directly proportional to the sines of the angles deflected.

Thus by means of a tangent or sine galvanometer, currents are easily comparable, and with a degree of accuracy only limited by the minuteness with which the angles themselves can be observed.

Reflecting Galvanometer

Another form of galvanometer is the Reflecting Galvanometer, in which the indications are directly proportional to the current passing through the instrument. The Reflecting Galvanometer consists, like all other instruments of this class, of a small magnet, so arranged as to move freely within a coil, consisting of a considerable length of fine insulated wire: the principle of action is precisely the same as in the detector, but there is a small mirror, attached to the magnet, which reflects a spot of light on a scale in such a way that, as you may perceive in the instrument now before you, a minutely small angle of deflection will, with the immense leverage, so to speak, given it by means of the ray of light, produce a very definite and easily read de-

FIG. 5.



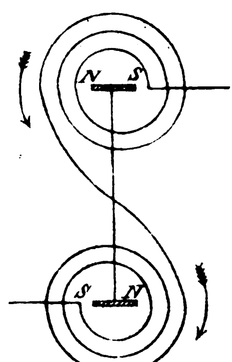
flection on that scale. For very small angles, the sines and tangents are almost directly proportional to the angles themselves ; with these instruments we may therefore take the currents as directly proportional to the deflections observed. They are designed especially for the measurement of very small currents.

In order to render these instruments extremely delicate, and they are infinitely more sensible to small currents than the sine or tangent galvanometer, the coils are formed, as in Fig. 5, with a very small opening indeed in the centre ; inside this opening a small magnet is hung, to which is attached a very light mirror, the whole (magnet and mirror) weighing but little more than one grain, is suspended by a very fine thread or fibre, in such a manner that the current approaches very near to, and acts very strongly on, the poles of the magnet : therefore, even with only a single magnet hung within the coil, the instrument is far more sensitive than the ordinary sine or tangent galvanometer, the magnet of which works on a pivot.

Astatic arrangement of Magnetic Needles.

In order to render these instruments still more sensitive, very frequently, as in the instrument now before us, there are two magnets, joined together by a thin rigid connector, as represented in Fig. 6, the north pole of the first and the south pole of the second, being ver-

Fig. 6.



tically one beneath the other in the same plane, and vice versa, and the wire so coiled round them, that the current tends to turn them both in the same direction, while the force of terrestial magnetism tends to turn them in opposite directions. This arrangement manifestly increases the delicacy of the instrument immensely, and indeed, with very small

magnets and a very long coil of wire, going several thousand times round them, there is scarcely any limit to the amount of sensitiveness attainable; in fact, with such an instrument, it is scarcely possible to complete the circuit, by pressing the two wire terminals together, without observing a current.

In my last lecture, I said that if a condenser or Leyden jar of any kind were charged with electricity and subsequently discharged through a wire, a momentary current, that is to say one lasting for an instant of time only, would be produced, and by means of this instrument, the effect of such a current is easily rendered apparent. We first charge the condenser, by connecting one plate of it with the pole of a battery, the second plate of the condenser and the other pole of the battery being connected with the earth; if we then remove the wire connecting the first pole of the battery with the condenser, the latter remains charged; if we now complete the circuit through the galvanometer, by attaching one end of its insulated coil of wire to the charged plate of the condenser, and the other to the earth, we get instantly a deflection of the magnet, a momentary deflection, produced by a momentary current, or in fact, by a discharge of the same nature as that which causes the spark, which we see drawn from a charged Leyden jar. The same result might also be shown if we were to attach the instrument to the charged condenser of the Ebonite Frictional machine in a similar manner; but if this condenser were highly charged, the violent discharge would probably fuse the fine wire in the coils, or in less sensitive instruments, destroy the insulation of those coils, by charring the silk.

Points to be attended to in the construction of delicate galvanometers

In making galvanometers of this nature, there are many points to be attended to. An important consideration is the best shape for the coils: they are better short than long, that is to say of considerable diameter as compared with their length, and fine wire should be used in the centre, next the magnet, with wires gradually increasing in diameter towards the outside. Again, it is very important that every part of the coil should be well insulated from every other part by good strong silk, which should be dipped in paraffine; indeed, the whole coil should, after a few thicknesses of insulated wire have been wound on it, be dipped in paraffine and baked in paraffine; then some more silk covered wire should be wound on, and it should be dried and dipped in paraffine again, and so on till the outside is reached, when it should be covered with shellac, so as entirely to prevent moisture from ever getting to the coil: during the manufacture and when complete, it should be carefully tested for insulation. The makers of these instruments are gradually becoming acquainted with these facts.

Quality of Copper used in sensitive galvanometers

For some purposes it is important that the copper, which metal is generally used for these instruments, should be of high conductivity, that is to say capable of passing a maximum of current, according to its sectional area, with a given electromotive force; for many purposes, however, this is not so very important. The conducting power of copper, that is of copper procurable from different sources, varies very considerably in consequence of the presence of more or less impurity in

the metal. It is especially important that no iron should be present in the wire used, otherwise successive deflections from the same current will not be similar, owing to the residual magnetism of the coil, which would behave like a small mass of soft iron.

Resistance of galvanometer must be proportional to that of circuit in which it is to be used.

One galvanometer will not answer equally well for every purpose, the resistance of its coils should always bear a certain proportion to that of the circuit with which it is intended to be used: for example, if we are dealing with a great resistance in any part of a circuit, a galvanometer of great resistance, that is to say formed of a great many turns of wire, should be used; if we are dealing with a circuit composed entirely of short thick wires, then the coils of our galvanometer should be also comparatively thick; and, in each case, we may pretty fairly estimate what will be the best kind of galvanometer to use in any given circuit, by taking the smallest resistance with which we have to deal, or the mean resistance of the various circuits we may be observing, and using a galvanometer which has a resistance nearly equal thereto.

Properties of German silver as used in the coils of galvanometers

For some purposes galvanometers of German silver are used. This metal possesses a very considerable electrical resistance, but it has also a very great advantage, viz., that its resistance does not alter much with temperature. We have seen that it is frequently necessary to take into consideration the resistance of the wire of the galvanometer itself, and when that resistance is continually changing, as is the case with copper coils, it becomes a matter of considerable labour to measure the resistance of our galvanometer, for the purpose of introducing it into our calculations; and as the resistance of German silver does not sensibly vary with a small change of temperature, when we have once measured the resistance of a galvanometer made with it, we may depend upon the value thus obtained, simply taking the precaution of checking it, about once in six months, by a comparison with a standard. For the purpose of measuring insulation, or of observing such a discharge as I have just shown you, the German silver galvanometer is quite as sensitive as a copper one; the only effect of the resistance being slightly to delay or prolong the current; the same quantity of electricity, that is to say the quantity collected or stored up in our condenser, must necessarily go round our magnet and produce the same effect, whatever the resistance of our coils may be; it is, therefore, a matter of indifference whether the coil is made of copper or German silver. In the one case, with the copper wire, we should have a very short current, of somewhat greater strength, and in the other, with the German silver galvanometer, we should have a rather smaller current, extended over a rather larger period.

Points to be attended to as regards the mirror and light.

There are various small points to which it is scarcely necessary to direct your attention: for instance, the mirror may be made slightly convex, so as to throw a well defined image on the scale, without the intervention of any lens, thus producing a more perfect spot of light, as well as obviating the loss, by absorption of light, in passing through the glass. Again, it may be made to hang in water, which does away with

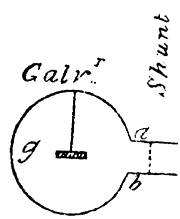
the perpetual swinging observable in the ordinary instrument. These instruments require a very bright light, and for this purpose paraffine is used; it is almost the only cheap substance which produces a sufficiently powerful light, and must therefore be carried about whenever these instruments are used. Gas does not answer the purpose nearly so well.

We have now seen how currents can be compared in any one given instrument; but suppose our favourite instrument was broken, or that we went to a different place, and thus got a different instrument from that which we had been accustomed to use in carrying out any series of experiments: how are we to know what is the ratio between the various currents we may have observed? If we have the two instruments side by side, the matter is simple enough, it is only necessary to pass the same current through each, and observe the different deflections produced on the instruments.

Shunts.

If one instrument is very much more sensitive than another, its sensibility may always be reduced, by means of an arrangement called a shunt, introduced into the circuit. Fig. 7 shows the principle on which

FIG. 7.



a shunt is constructed: if *a g b* represents the main coil of a galvanometer, and we introduce a short coil between the two terminals *a* and *b*, with a resistance of $\frac{1}{9}$ that of the main coil, we know, by the laws of electrical currents, that $\frac{9}{10}$ of the current would pass through the smaller resistance, between *a* and *b*, and $\frac{1}{10}$ only through the coils of the galvanometer. Similarly we might diminish the current, passing through any given galvanometer, to $\frac{1}{100}$ or even $\frac{1}{1000}$ of the whole, by shunts equal to $\frac{1}{99}$ or $\frac{1}{999}$ of the galvanometer coil. These little coils, called shunts, are so arranged, that by them, we can diminish the proportion of a current passing through a galvanometer to any amount required; they allow very sensitive instruments to be used in measuring large currents, since by reducing the proportion of the currents passing through the galvanometer, a corresponding reduction is made in the deflections of the magnets, which are thus brought within workable limits; and when we have measured the thousandth part of a powerful current, we have measured the current itself, having only to multiply the observed current by 1000. By means of shunts, it is possible to compare any two galvanometers, which may differ very considerably in construction and in consequent electrical resistance and in sensibility; for we may arrange our shunts so that only some small

known portion of the whole passes through the more sensitive instrument, and can therefore use a comparatively strong current, to deflect the less sensitive instrument.

Variation in sensibility of galvanometers

There is, however, another point to which I must direct your attention, viz.: that we have no certainty that the same galvanometer will retain its sensibility unaltered for any considerable time; for instance, we know that the two magnets may vary slightly in their sensibility, and the resultant directing force, even of constant terrestrial attraction, would then of course vary likewise, so would the deflecting force of a constant current, but not in the same ratio. Again, supposing the magnets to remain constant, or that we have but one magnet in our galvanometer, the directing force of the earth varying from day to day, we should not get comparable results; for, while the directing force varied, the deflecting force of a constant current on the constant magnet would remain constant; and further, the force of terrestrial magnetism varies very considerably indeed in different parts of the world; it is impossible, therefore, by carrying about even a constant instrument, when part of that instrument is a magnet, to be certain that currents, which we may observe in different parts of the world, or even at different times in the same place, with such an instrument, bear the relative proportions to each other, which the deflections of the magnet may seem to indicate with the tangent or reflecting galvanometer. A variation in the magnet does not very much matter, because the action of the current upon the magnet is increased precisely in the same ratio as the action of terrestrial magnetism thereon, so that the only change is due to a change in the directing force of the earth's magnetism, and that change is only slight in any one given place. Thus, if in a given instrument the single suspended magnet lost half its magnetism, it is quite true that any given current would only act with half the force to deflect it, but then this would be resisted only half as much as before, by the action of the earth on the enfeebled magnet, so that the deflection would remain as great as when the magnet had its full strength, provided we may neglect the torsion of the suspending fibre. This does not apply, as already explained, to astatic galvanometers. All instruments in which the directing force of the earth is supplemented by an external magnet are very inconstant.

Marine reflecting galvanometer.

Another form of the reflecting galvanometer is intended for use at sea and, being very much more portable than the ordinary form, would also be found useful for Military Electrical operations. In the ordinary reflecting galvanometer the little magnet and mirror are continually moving about, the slightest jar disturbs them and, from the extremely delicate nature of the fibre on which they are suspended, great care is necessary to prevent the magnet breaking loose. It is indeed a very fragile instrument, and I have had no slight anxiety in bringing that, which you now see before you, the very short distance from London to this town. We have, however, another arrangement of exactly the same kind, which is not liable to be broken: it consists of the ordinary coils, which I have so frequently described to you, within which is

placed a small slide, and inside that slide a minute mirror and magnet, strung or attached to the slide by a very fine fibre at the top and bottom, so that, although the fibre is slight, it is yet not liable to injury, and no amount of jarring will cause that fibre to break; the magnet and mirror, not being free to move in any direction except round the axis along which the fibre passes, never falls with a jar on that fibre, which is made amply strong enough to carry their simple weight; moreover, the fibre passes accurately through the centre of gravity of the mirror and magnet, in other words, they are so balanced that no motion, in any direction, causes them to deflect either to one side or to the other, and this is a very great advantage, because however much a ship may roll or pitch, such a mirror will always remain in a perfectly neutral condition, directed by an external magnet, of considerable strength, so placed as immensely to exceed the directing force of the earth; these arrangements maintain the spot of light invariably at zero until a current passes through the coils. The sensibility, which is necessarily inferior to that of the land (single suspension) instruments, may be much increased, by placing the whole instrument inside a very thick wrought iron case, the effect of which is to deflect the magnetic lines of force due to the earth and render them extremely weak inside that thick shell of iron. I think it would be possible to make this iron shell so thick, and so completely to cover in the magnet, as to leave no sensible force, due to terrestrial magnetism, whatever in the centre; it is however necessary to provide some slight directing force, and for this purpose, a small horse-shoe magnet, which just gives sufficient directing force to bring the mirror and magnet always back to a constant position, is provided within this iron sheath. When put together, therefore, the whole instrument can be moved about in any direction, while the magnet and mirror, and the spot of light reflected from it, will remain in a constant position on the scale, till the current passes through the coil. The only defect of this instrument is its great weight, which is comparatively enormous, on account of its thick iron covering, but, leaving this out of the question, it can be moved without great chance of injury, and is therefore superior in many ways to the ordinary form of reflecting galvanometer.

Differential galvanometers.

Before proceeding to the consideration of another and totally distinct class of instrument, by which I shall be able to show you that we can definitely measure currents, with the certainty that we are obtaining the same result to-day that we did yesterday, or the same result in any distant part of the globe, in India for example, that we do in England, I wish to direct your attention to another form of galvanometer used to compare, though not to measure, currents, viz.—"The differential galvanometer." The principle of this instrument is simply that instead of having one coil of insulated wire wound round the magnet, we have two, two distinct circuits, made as similar as it is possible to make them, so arranged that they shall exert exactly similar forces, in opposite directions, upon the magnet suspended in their centre; thus, if we pass one and the same current round the two

coils, in opposite directions, we ought to get no deflection whatever of the needle, however sensitive the instrument may be, and it is not very difficult to make such a galvanometer. If we take two wires of equal diameter and similarly insulated, and wind them on together on one and the same coil, taking care that each wire goes an equal number of times round the magnet, and join them end to end, in such a manner that the current produced by any given battery may pass through them in opposite directions, we should have, if the coils are exactly equal and equidistant from the magnet, no deflection; as, however, in practice it is almost impossible to make the coils so exactly equal as to produce this result in the first instance, it becomes necessary to correct any small deflection that may occur, by adding a few more turns of wire to one or the other of the coils, till that deflection disappears. When this is done there may still remain a slightly different resistance between the two circuits, which must be corrected by adding a small resistance coil, completely outside the instrument, where it will have no deflecting action upon the magnet. By the above operation we form an instrument, consisting of two perfectly similar circuits, having the same resistance, and exerting an equal force upon any magnet, suspended freely within its coils, and we may be perfectly certain that any two currents which produce no deflection of the magnet, when passed through these coils in opposite directions, are really equal. Instruments formed in this manner are called Differential galvanometers, and they give far more accurate results than those which depend upon the observation first of one and then of another deflection, because the accuracy to which the differential method can be carried is so great, that a difference of not more than one part in ten thousand would be detected, whereas a deflection can hardly be observed with greater accuracy than one part in five hundred. The Differential Galvanometer is therefore, for many purposes, extremely useful. By the use of shunts, unequal currents of any ratio, can be directly compared; by observing the shunts required to balance any two unequal currents, their ratio can be determined.

Comparable measurements of currents with various galvanometers

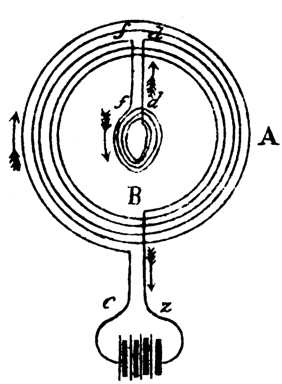
To return to the problem of obtaining comparable measurements of currents with various and varying galvanometers. The following is a simple, though indirect method, of determining how far the indications of a galvanometer are constant. We may observe what deflection an instrument gives with one Daniell's cell and a given resistance, or what resistance might be required, in the whole circuit, to produce a unit deflection with a single Daniell's cell, using shunts to exclude a given proportion of the current should it prove too strong; this is perhaps the most practical method of ascertaining the constancy of the reflecting galvanometer, and for all practical purposes, it is sufficiently accurate; the resistance thus observed, as necessary to produce the unit deflection in a given instrument with the single Daniell's cell in circuit, is frequently called the constant of the instrument. For scientific purposes the above method is not sufficiently accurate, because the Daniell's cell itself does not, strictly speaking, produce a constant electromotive

force, it may vary to the extent of from one to four, or even five per cent., so that any comparison of galvanometers made in that way, cannot be supposed to be more accurate than, perhaps, within two or three per cent. of the truth. This consideration led to the invention of a totally distinct class of instruments, which are called Electro-dynamometers.

Electro-dynamometers

The principle on which an Electro-dynamometer is constructed is, that the effect observed shall be produced by the action of one part of a current upon another part of the same current, and no magnet whatever is employed in the instrument. Fig. 8 represents the oldest and simplest form of this instrument: it consists of a coil of wire A, similar to that of the tangent galvanometer, and within that coil of wire is suspended, by means of two fine wires *d d* and *f f*, a small roll of wire B. In this instrument the current passes from the positive pole of the battery any convenient number of times round the large coil A, down into the small coil B, round that small coil a certain number of times, back, by the other suspending wire, to the large coil, and thence to the negative pole of the battery: thus, one and the same current passes through the fixed large circle, and the suspended and moveable small circle. This small suspended circle should, in its condition of rest, stand in the magnetic meridian, so as to be unaffected by the earth's magnetic force, and it should also be perpendicular to the plane of the large circle. When a current is passed through this instrument, it tends to bring the small circle into a plane parallel to that of the large one, and the amount of force exerted to effect this is, of course, proportional to the square of the current which is passing through the two coils: the instrument should be so arranged that the larger coil may be turned round so as to bring the smaller one invariably into the plane of the magnetic

FIG. 8.



meridian, while the current is passing, so as to eliminate the effect of terrestrial magnetism on the smaller coil. We have thus an instrument entirely independent of magnets, and simply acting in accordance with the laws which regulate the action of one part of a current upon another part of the self same current, its indications will therefore always remain constant as long as the torsion and distance of the suspending wires, which alone supply the directing force, remain constant.

This same idea can be worked out in various ways, for instance, instead of using the bifilar suspension, we may string the small suspended coil on one single wire, in the same way as the magnet was suspended in the marine galvanometer, or we may place the small suspended coil between two large flat coils, through which the same current is made to circulate. The force exerted, between the suspended and the fixed coils, is thus greatly increased by the proximity attained; and in this and other ways, the sensibility of such arrangements, as I have described, may be increased.

The great value of these instruments consists in their being quite independent both of terrestrial magnetism and of steel magnets; they are therefore independent of all those variations necessarily arising in any arrangement of which a magnet forms a part, and their indications will therefore be constant; so that wherever carried, if we get the same deflection, indicating the same force, we may be quite certain that that deflection and that force are produced by the same strength of current.

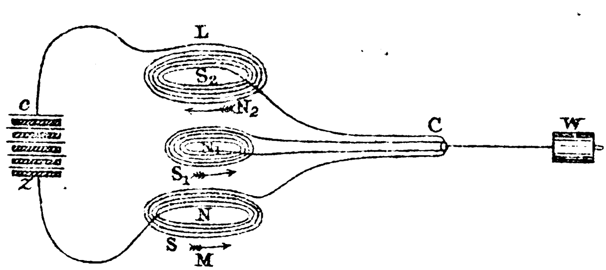
In order to compare instruments of this construction it is therefore evident, that it is only necessary to compare them once for all and, if we have a standard Electro-dynamometer so made that we can, from its deflections, calculate the value of the current in that absolute measure, which I endeavoured to explain to you in my last lecture, we shall be able to affix a co-efficient to every dynamometer which is sent out and, by simply multiplying the deflection observed in any particular instrument by the co-efficient accompanying it, we shall be able to reduce that deflection into an expression referring to, or measured in, one and the same unit. Thus, if an instrument of this nature, with its accompanying co-efficient, were sent abroad and used, in the manner above described, for comparison of currents, it would be only necessary, in sending the results of experiments home, to say currents of so many units were observed and this statement would be perfectly intelligible to the person receiving it. It is only by means of an instrument of this nature, that we can make any approach to such accurate information as is desirable, in the observation of various currents, for certain purposes. I may add, that a standard instrument of this sort is now being made, though not yet quite complete: when it is complete copies will be prepared, by comparison with it, which may be used in precisely the same manner as we now use the ordinary Resistance coils, which give us accurate measurements of Electrical Resistance in terms of the standard unit universally adopted and, by means of an Electro-dynamometer and a simple co-efficient, we shall be able to measure currents in standard units, which will be the same as those

employed by all other observers, which in itself will be no small advantage.

The mode in which a standard instrument of this nature, capable of measuring currents in that apparently complicated manner, to which I alluded in my last lecture, is constructed, is somewhat as follows.—The instrument is almost exactly like that which I first described by reference to Fig. 8: you may remember that I said that a unit of current, acting through a unit length, say one foot, of wire, bent into a circle, upon a unit pole of a magnet suspended in its centre, was productive of a unit of force, and, I have pointed out, that instead of the unit pole of a magnet at the centre, we might use a small coil, taking advantage of the known laws of induction between one part of a current and another part of the same current. We can calculate the force that ought to be produced on the coil, suspended at the centre, by a given current, and we can calculate the directing force that should be given by such a suspension as we have here, by means of two wires, *f f* and *d d*, Fig. 8, and we then get a very simple expression of the result, namely, that the force of the current is equal to the square root of the tangent of the angle of deflection, multiplied by the product of two constants. These constants are themselves equal to two rather complex expressions, which only involve, however, measurements of length, time and mass. These measurements are simple, and the expressions, though long, are not very complicated, and the observations required do not take much time to make. It is not, therefore, a very difficult matter to make this standard instrument, which is now actually in course of construction, and, when once it is made, it will be unnecessary to trouble observers with any complicated formulæ, as each instrument will be accompanied by its own co-efficient, obtained by comparison with the standard, by which its indications may be multiplied and thus the value of any current passing through it, may be obtained in terms of the standard unit previously determined.

Construction of a standard dynamometer.

FIG. 9.



The sort of instrument which will probably be used for general purposes, is shown in Fig. 9. We shall have a small flat coil, N_1 S_1 round which the current to be observed circulates. This coil is carried by an arm centred at C and balanced by a counterbalance W. The support at C may be on knife edges, or it may be a simple wire on which the arm is strung. Now, if that small flat coil were placed between the similar poles of two magnets, placed at L and M, and the current, which flowed through this coil, were such as to produce a north current on its upper side, and a south current on its lower side, then the north pole at the top would be repelled by the north pole of a magnet at L, but the south pole would be attracted by the north pole of the opposite magnet at M: thus, if this little coil were moveable between the poles of these two very powerful magnets, it would indicate the passage of the current by the motion of the coil, and the force, producing this motion and due to the passage of a current, might be indicated and measured by some such mode as the torsion of a wire, the lifting of a weight such as the counterbalance at W, or other simple mechanical arrangement. If the direction of the current through the coil were reversed, the coil would be lifted instead of being depressed. Such an instrument would, in point of fact, constitute an extremely sensitive galvanometer. Now here, as in the ordinary galvanometer, we introduce coils and magnets, but with a very considerable alteration as regards any arrangement previously described, for the magnets, which were before small and moveable, are now large and fixed, and what was before fixed, namely, the coil, has been made moveable. Thus, though the parts are in a very different position from those in the ordinary galvanometer, the force produced by the passage of a current, would be of the same nature as that, exerted under similar circumstances, in the ordinary galvanometer.

Now, instead of these two large permanent magnets, let us suppose that we take the actual current to be observed, and pass it round two coils, wound upon pieces of soft iron, in such a manner as to produce two electro-magnets, with similar poles on opposite sides of the moveable coil, as at L and M, Fig. 9, then we should have the same result as that in the arrangement formed with the two permanent magnets; but now, let us omit the soft iron altogether as an element of uncertain action, we shall still obtain a force, due to the passage of the current, of the same kind and in the same direction as before; true, that force will be feebler, but the indications of the instrument will be constant, being produced by the current acting on itself without the intervention of any iron or steel magnet whatever. We need only take care that the directing force, whether it be a weight or a wire, shall be constant. The reason why such a form as this is preferable to Weber's dynamometer, is that, in this arrangement, the coils can be brought very close together so as to produce comparatively a very much stronger force for the same current and, consequently, a more sensitive instrument. But I am here rather speaking of what will be done some day, than of what

has been already accomplished. Although these arrangements and plans have not been fully carried out as yet, in all probability they will be within the next year; and I hope that, in the course of time, perfectly accurate measurements of electric currents may be practicable and as readily made as the accurate measurements of resistance already in use.

NOTE.—The measurement of a steady current, in absolute measure, by Weber's dynamometer, with a bifilar suspension, may be made as follows:

$$C = \sqrt{\alpha . \beta \tan \theta} \pm H . \gamma \tan \theta + \text{smaller corrections.}$$

The instrument is placed so that the plane of the fixed coil is in the magnetic meridian, and that of the suspended coil perpendicular to it.

θ is the observed angle of deflection, due to the current C, α is a quantity depending on the force of restitution and is equal to $4 \pi^2 \frac{M . k^2}{T^2}$, where $M . k^2$ is the moment of inertia of the suspended coil, and T is the observed time of a complete vibration of the coil, as suspended. T should be observed frequently in the course of experiment. The best way to determine $M . k^2$ is to prepare a body of simple form, whose weight and radius of gyration are not very different from that of the coil. (A flat ring, of weight M and mean radius k, is best).

A steel wire is then prepared with a light suspension apparatus, which can support the coil in the position it has when suspended, or the ring in a horizontal position. Let the time of vibration of the coil, when suspended from the steel wire, be T_1 let that of the ring be T_2 and that of the suspension apparatus T_3 Then if $M . k^2$ be the moment of inertia of the coil, M^1 the weight of the ring in grammes, and r_1, r_2 its outer and inner radii

$$M . k^2 = \tfrac{1}{2} M^1 (r_1^2 + r_2^2) \frac{T_1^2 - T_3^2}{T_2^2 - T_3^2}$$

In this way $M . k^2$ may be found once for all. The quantity β in the equation, ($C = \sqrt{\alpha . \beta . \tan \theta} \pm H . \gamma . \tan \theta$ + smaller corrections), is $\beta = \frac{\rho^3}{2 \pi^2 . N . n . R^2 . r^2}$, where N and n are the number of windings in the great and small coils respectively. R and r their radii. ρ the distance of the large coil from the centre of the instrument, which is greater than R if Gaugain's plan is adopted.

H is the horizontal intensity of magnetism $\gamma = \frac{\rho^3}{4 \pi . N . R^2}$

The positive or negative sign of the small correction must be taken according as the current, in the small coil, tends to bring it back to its normal position or to increase its deflection.

If our readings are taken corresponding to the reversal of the current in both coils, the H correction will be nearly got rid of.

LECTURE III.

ON

ELECTRICAL MEASUREMENTS,

DELIVERED BY

FLEEMING JENKIN, ESQ., F.R.S.,

At the Royal Engineer Establishment, Chatham, on the 25th February, 1867.

WRITTEN BY

CAPTAIN R. H. STOTHERD, R.E.,

AND CORRECTED BY THE LECTURER.

The methods for comparing and for the better measuring of currents, which I had the honor of describing to you in my last lecture, are applicable only to permanent currents, currents too which do not vary during the time they are being measured. When a current varies rapidly, or lasts only for so short a time as not to produce a constant effect—such an effect as can be measured in the way described in my last lectures—we must have recourse to totally different methods of observation, and are then driven to observe quantity only. You will remember that, as I defined the strength of a current to be equal to the quantity of electricity which it conveyed in a given time, so we can compare currents which last for only a very short time, provided we have the means of comparing or measuring the quantities of electricity which those currents convey. My lecture to-night will therefore be directed, first to the explanation of the methods by which quantities of electricity can be compared and measured, and secondly, to the method by which the capacities of certain bodies for containing a certain quantity of electricity can be compared and measured.

Measurement of Currents of short duration.

When a current of very short duration flows through a reflecting galvanometer, it gives an impulse to the needle, which causes it to swing rapidly to one side, and then return and oscillate from side to side, till it gradually loses the impetus given it in the first instance and resumes its position of rest, provided no new impulse, dependent on a

new current, is given it by passing the latter through the instrument. Now from the amount of this first swing in any given instrument, we can calculate the force which was required to produce it, and we can therefore calculate the total quantity of electricity which produced that force. You may remember that I told you, that the force produced by a current is proportional to the strength of the current and therefore to the quantity of electricity it conveys. Now as regards the total quantities which pass, (in a very short time), through a given galvanometer in two cases, producing two different deflections, the force exerted and the current exerting the force are proportional to the sines of half the angles observed. On the passage of the first current the needle swings to a certain angle which we observe, say 20°, and on the passage of the second current we observe that the impulse causes a momentary deflection of only 10°, thus the quantity of electricity which passed through the galvanometer in the first case, was to that which passed in second case, as 0·174 to 0·087, these numbers being the sines of 10° and 5° respectively, and the quantities are not proportional to the corresponding angles, nor to the sines of the angles, but to the sines of half those angles.

The proof of this proposition is as follows. The swinging mass may be considered as a ballistic pendulum, receiving a short impulse, due to the current conveying the quantity of electricity discharged through the galvanometer. The force exerted will be in proportion to the quantity, and so, cæteris paribus, will be the velocity v, of the centre of oscillation of each half of the magnet, looked upon as a double pendulum. The velocity will, as in the case of the ballistic pendulum, be proportional to the sine of half the angle of deflection.

Thus we have a very simple method indeed of comparing the total quantities of electricity, which are conveyed by currents of short duration. This formula is based upon the assumption, that the impulse given to the needle is very short indeed, as compared with the time of the oscillation of the needle, it implies that the force has acted as a blow, a sudden shock or impulse on the needle, when that needle was parallel, or nearly parallel, to the plane of the coils surrounding it; in using this formula, therefore, it is necessary to have a galvanometer, the needle of which swings slowly, and a comparatively heavy needle, suspended by a very fine fibre, is the best to use for the purpose. Another point to be attended to, in making use of this method, is, that the form of the needle shall not be such as to cause the air to offer a great resistance to its movement, for the formula supposes that the needle swings quite freely, and without meeting with any resistance on the part of the air:—in the instruments, therefore, in which the needle, being itself very light, is attached to a comparatively large mirror, the formula will not be found to apply with any great exactitude, because at each swing, the oscillation is diminished so very much, in consequence of the resistance of the air, that the impulse, produced in the first instance, does not send the needle so far as it would if the air were absent. When the air offers only a very slight resistance, a small cor-

rection of a very simple nature may be introduced; in the first deflection of the needle, we observe the oscillation to one side of the zero point, say an angle of 20°, we then note the angle to which, by the action of its first oscillation, it returns on the same side of the zero point after one complete oscillation, say 19°; this difference is caused solely by the friction or resistance of the air and we may fairly argue that, had the air not been present, the first impulse would have carried the needle beyond the point observed, by the amount of one quarter the difference between the oscillations on each side of the zero point, and that the true angle would, in this case for example, be not 20°, but 20° 15′, the air having, as a matter of fact, caused a decrement of 1° in passing from its extreme limits of deflection, say from left to right and back again. We may assume that it would have caused a decrement of 15′, or one quarter of a degree in passing through the distance from the centre to the left.

If this correction be introduced and care be taken to obtain very accurate observations of the angles to which the needle of a galvanometer is deflected, this method of comparing small quantities of electricity, or currents of very short duration, will be found to be extremely accurate.

Apparatus applicable for the measurement of short currents, produced by Magneto-induction apparatus.

This method of measuring currents is useful in comparing the instantaneous currents, induced by the revolution of an armature in front of the poles of a magnet, on which an arrangement of coils wound on soft iron cores has been placed in the usual manner. We know that, as the armature above mentioned revolves, a series of instantaneous currents of electricity is induced in the fine wire coils, in one direction as the armature approaches the opposite poles of the magnet, and in an opposite direction as the armature recedes from those poles. Now, by the method just described, we can observe a single one of these currents, produced by a single motion of the armature, and thus ascertain, with great accuracy, under what circumstances we obtain a maximum of effect. Again, we know that fuzes of a certain nature are fired by a single short current of electricity passed through them; now, by the means described, we could measure, or rather compare, the quantities of electricity, necessary for fuzes of different construction, arranged to be fired by a single short current in this way, or for the same fuze or kind of fuze under different conditions.

We have thus also the means of comparing the different quantities of Electricity, required to produce certain physiological effects.

Precautions to be attended to in measuring currents of high potential.

When currents are produced from condensers, by a short discharge, and when those condensers have been charged with electricity of very high tension, as for example with that generated by the Frictional machine, it is necessary to take special precautions in the construction of the galvanometer to be employed, in consequence of the peculiar action of a charge of electricity of such a nature. Electricity, at what I should call a very high potential indeed, is apt, in the ordinary galvanometer, to burst its way through the insulation of the coils from one wire direct to the next convolution of the same, burning the silk

or other intervening insulating substance, and destroying the instrument; moreover, if the entire charge does not pass round and round through the whole length of the coils of a galvanometer, we do not obtain a true measure of the total quantity: therefore, in measuring currents, produced by charges from a frictional machine or other agent, generating electricity of high potential, we must wrap the wire in a double coating of silk, and take care to dry it (the silk) thoroughly and imbed it in paraffine, in fact take all the precautions adopted, in forming the secondary coils in Rhumkoff's coil apparatus.

Measurements of short currents in absolute units.

I have now explained how quantities of electricity can be compared, by their discharge through a galvanometer, but a comparison is still very far from being a measurement, and a measurement, in any arbitrary unit, is very far from being a measurement in those units, to which I alluded in my first lecture. Fortunately, however, a very simple formula gives us the means of reducing the observations on any given galvanometer into measurements, in terms of those so called absolute units, viz.: $Q = \frac{2. C. t}{\pi} \text{Sin.} \frac{1}{2} \theta$, Q being the quantity, C the current, (in absolute measure), which would produce the unit deflection upon the particular galvanometer used, that is to say a deflection of 90° on a sine galvanometer, or of 45° on a tangent galvanometer, or of one division on a reflecting galvanometer; t is half the period, or time of a complete oscillation of the needle of the galvanometer when swinging freely, if not directed or deflected by any current, and θ the angle of deflection due to the quantity Q. I explained, in my last lecture, how it is possible to find C, and all the other components of this equation are easily understood and involve very simple observations, and they give us the total quantity of electricity in terms of absolute measure. It is easy to see the meaning, so to speak, of this formula, the amount of the current which will produce the unit deflection is a measure, as it were, of the sensibility of the instrument: if a very small current produces the unit deflection, the total quantity, which corresponds to any given deflection, is necessarily small; on the other hand, the angle deflected serves to compare the various effects produced upon any given instrument. t being the time taken by the needle to swing or oscillate, when it is suspended freely, depends on the inertia of the needle; if we have a heavy needle, the oscillation will occupy a comparatively long time, if on the contrary we have a light needle, its oscillation will be more rapid and it will be capable of being moved by a comparatively small force.

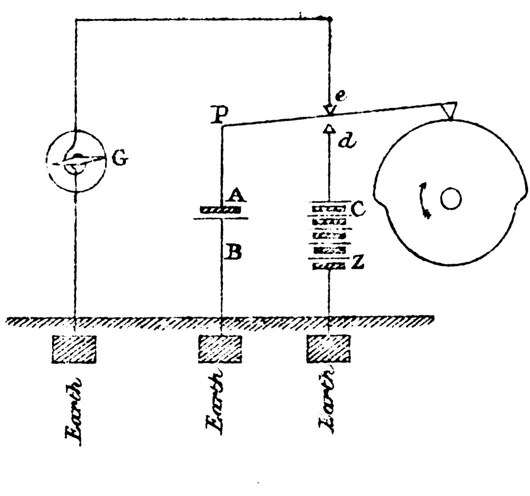
There is a second formula, viz.: $Q = \frac{k}{\pi^2 . n} \text{H}. t. \sin \frac{1}{2} \theta$, where $k =$ the radius of the coil, $n =$ the number of turns made by the wire round the coil, $\text{H} =$ the horizontal component of the earth's magnetism, in absolute measure. This affords the means of measuring the quantity, in terms of the horizontal intensity of the earth's magnetism, which is, however, a comparatively troublesome thing to measure, and

the formula is consequently less simple in application than the former one.

Measurement of a succession of short currents.

When short currents can be continually repeated, there are several other methods by which they can be compared. Hitherto I have spoken of a single very short current, produced by a single quantity, but there are many cases in which it is possible to reproduce continually, exactly the same quantity of electricity and pass it through the same wire. We do not thus produce a perfectly continuous permanent current, but we produce a succession of shocks, following each other with such extreme rapidity, that the effect on a galvanometer needle is precisely the same in outward appearance, as if we were pouring one continuous stream of electricity through the instrument. When that is the case we can measure this sensibly permanent current, and by dividing the total quantity, per minute or per second, conveyed by a current of that strength, by the number of small discharges, or, in other words, by the number of small currents which we send through the instrument in that time, we get the total quantity due to each short current. This is a method which is very much used in practice, and its effect is easily seen by the use of a small arrangement, which enables us to make and break contacts with great rapidity. Fig 10 shows a simple form of an arrangement of this kind. Suppose C Z to be a battery, one pole of which, Z, is connected to earth and the other to the terminal *d*, and let P be a key or spring, working between this terminal *d* and another terminal *e*, the latter being in connection with a galvanometer G, and through it to earth at the point F : if this key P be connected with one plate A, of a condenser or armature of a Leyden jar the other plate, or armature B, being connected with earth, it is evident that, when the key is pressed

Fig. 10.



down and in connection with *d*, the battery will charge the condenser with a certain amount of electricity, and, when it is raised and brought in contact with the point *e*, that same quantity will be discharged through the galvanometer to earth. When the key is again depressed, the condenser will again be charged with an equal amount of electricity, because all the other conditions will be the same; and when it is again raised to *e*, an equal amount will again be passed through the galvanometer; consequently if we work the key rapidly up and down, at a uniform rate, the condenser will be rapidly charged with a succession of equal quantities of electricity, which will as rapidly be passed through the galvanometer to earth, producing a single permanent deflection, like that due to a permanent current. By means of clockwork, an arrangement of this nature can be made, by which an extremely rapid and uniform succession of currents—say 10 per second—may be first transmitted to the condenser, and thence through the galvanometer to earth. The number of discharges per second, required to produce a sensibly permanent deflection, will vary with the time of oscillation of the needle of the galvanometer; with a heavy slow needle comparatively few discharges per second are necessary. In all cases the time occupied by each discharge must be a small fraction—say $\frac{1}{100}$th of *t*.

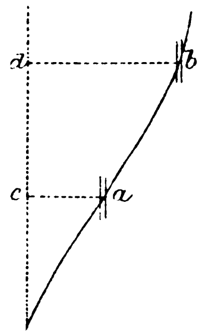
The above is one instance of a succession of perfectly equal short currents produced by equal quantities of electricity. Another would be that of an induction apparatus, revolving in front of the poles of a magnet; we know that every time the armature passes before the poles of the magnet, a short current is induced, and that every time it repeats the passage a similar current is induced, because all the circumstances of the case are absolutely unaltered, and all these short currents may be so summed up as to produce one long permanent current. If then we measure that current, and divide it by the total number of induced currents which we have obtained, we get the total quantity in each of these induced currents: therefore when we can do this, we have clearly a second method of comparing currents of this nature in addition to the method by a single swing. The rapidity with which these small currents can be produced is very great, the apparatus now before us is constructed to send a series of short currents, some 600 per minute, each of them lasting, however, only about the thousandth part of a second, but producing a permanent result, on a galvanometer, of a perfectly well defined nature.

Measurements of varying currents.

Another use, to which this method of making and breaking contacts at regular intervals may be applied, consists in the measurement of any varying current. Let us suppose that a current of electricity is not constant, but that it begins from nothing and gradually increases to a maximum, according to some certain law which we do not know, but which we wish to discover. The whole variation or gradual increase, which takes place in such a case, will probably occur in a comparatively very short time: you must, however, remember that no current of electricity whatever reaches its maximum in an infinitely

short time ; like many other things, it begins small and grows very rapidly (in the case of such a current), to a maximum. Now when these short, but continually varying, currents can be produced, in constant unvarying succession, so that we may feel quite certain that, whatever they may be, they are always alike, we may so arrange a little key, such as that shown at the point P, in Fig. 10, that it shall take out a small part of the current for a very short time. Let us suppose the curve, shown in Fig. 11, to represent the gradual increase

Fig. 11.



of a current, commencing at nothing and gradually increasing to a maximum Now if at the point (a), $\frac{1}{10}$ of a second after the commencement of this current, we shunt a portion—say $\frac{1}{100}$ thereof, through our galvanometer for a period of $\frac{1}{1000}$ of a second, and if we then cut out the shunt and allow the current to reach its maximum, to complete its cycle of operations, to commence again at nothing and come round, so that it shall have reached precisely the same strength as before, and again shunt another small section of the current for $\frac{1}{1000}$ of a second, and, having arranged our apparatus, so that it shall continue to shunt a series of small sections of a current of this nature of precisely similar strength, as for example 10 or 20 times in a second, and if equal currents are produced at these intervals, we shall then obtain a sensibly permanent current, indicated on the galvanometer, the strength of which will be proportional to the strength of this main current, from which it is derived at the moment of the derivation; again if we vary our arrangements so as to shunt a second little section, of $\frac{1}{100}$ of the current as before at the point (b), $\frac{2}{10}$ of a second after its commencement, and dispose our apparatus as before, we shall get a new permanent current, but it will be a very much more powerful one than that which we obtained at our first point (a), and it will be as much more powerful, as the co-ordinate (b d) is greater than (a c). Thus by trying this experiment at different times, after the commencement

of the current, we shall be able to discover the proportion between the successive ordinates and therefore the law, according to which that current increases from nothing to a maximum. What we really observe, in each of these cases, is the accumulated effect of certain small equal quantities of electricity.

It may be observed that, in shunting a small portion of the whole main current for a short time, we need not sensibly alter any part of the circuit; the shunt will only slightly diminish the resistance of the circuit for a very short time.

Applicable to observation of currents arriving on submarine lines.

This method is actually applicable to the gradual arrival of signals through land lines, but the experiment is more easily made on a submarine cable of moderate length, where the signals arrive more slowly. It could also be applied to the measurement of a current in any induction apparatus: as the armature, in any magneto-electric combination, passes the magnet, a current is induced which begins from nothing, increases to its maximum and falls again to nothing, and the law, according to which that increase takes place, could be observed by this method. I am now occupied in giving you methods, by which you may be able to make observations for yourselves at any future time: I am not simply teaching you practical results already attained, but rather trying to show you how you can discover these things for yourselves.

Points to be observed in the use and construction of these instruments.

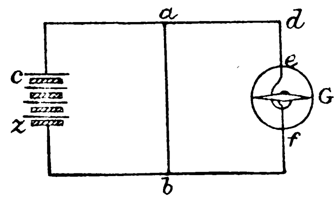
In constructing an apparatus of this sort, great care is required in order to ensure really good contacts on the part of the little key or tongue, which is made to oscillate so very rapidly, and a great many different plans have been tried for this purpose. One of the simplest would appear to be to make a cam upon a shaft, which will work the little key up and down. By this method good contact is certainly made in one direction, as in Fig. 10 for example with the upper piece of brass or platinum (*e*), but when the little key works in the other direction, the spring is frequently not found strong enough to move it with sufficient rapidity and contact is not made though, in using such an instrument, we may suppose we are making it, and from this cause fallacious results are frequently obtained. Another method, which has been tried, is to alternate pieces of vulcanite and brass or platinum, so as to make a series of perfectly smooth contacts; the defect in this case is, that the vulcanite is liable to be spread or smeared over the brass or platinum and the contacts thus injured. Again, if the vulcanite is omitted so that the spring or key rubs over a succession of teeth or projections, separated by an air space, a vibration is set up in the spring, which is almost certain to produce what is called "chattering," an effect which is sometimes seen in the relay of the Morse recording Telegraphic Instrument or in similar arrangements, the tongue not making perfect contacts but vibrating, as it were, over the point of contact. All these difficulties may cause fallacious results. In the instrument now before you, a plan has been adopted, by which the spring is held quite tight in both positions of contact, by a small wheel arranged in a peculiar manner. The spring or contact piece here moves sideways, between two half rings, which alternately press it against one

and the other contact, so that at no period of the revolution is the spring free to chatter, and the rapidity of the motion of the spring is independent of the strength of the spring itself, being wholly governed by the speed of rotation of those central cams. This difficulty as to rapid contacts thus overcome, we can produce currents, from the accumulations of our small quantities of electricity, and compare those quantities, by any of the means which are used to compare the continuous currents produced in the ordinary way, by battery power. We can thus observe the actual deflections, in the way I have already described, by means of one galvanometer, or we can observe the two sets of currents, to be compared by means of two galvanometers, of known relative sensibility, or through a differential galvanometer, by balancing them, one being partly shunted from the second coil of the instrument. These are the methods, described to you in my previous lectures, and by them, when we can obtain an accumulation of these little quantities sufficient to produce a permanent current, we can measure the current and so the quantities of which it is made up.

Arrangement of Chronoscope.

One further application of the measurement of a quantity of electricity may be interesting to you. It is one by means of which you might, I think, construct a very sensitive chronoscope, for the measurement of a very short period of time, such as that occupied by the passage of a bullet, between two points in its course, when fired from a gun. This has not been actually tried yet, so I must speak of it with some diffidence, but it is well worth a trial. In Fig. 12, suppose one pole (*c*) of the Battery (*c z*) to be connected with the terminal of a galvanometer (G), the other terminal (*f*) being connected with the other pole (*z*), the circuit would be completed, through the galvanometer, by the conductor (*c a d e f b z*): now suppose we place a short thick conducting wire (*a b*), between the battery and galvanometer, that is to say in such a position as to offer a much shorter and easier path for the current, produced by the battery, to complete its circuit, without passing through the coils of the galvanometer; now by Ohm's law, the current generated by the battery will divide itself at the point (*a*), and pass along the two paths open to it inversely in proportion to the resistance of these two conductors (*a d e f b*) and (*a b*), and, if we so arrange that the resistance of (*a d e f b*) shall be very much greater than that of (*a b*), the current passing through the galvanometer may be so small as not to deflect it visibly: if, for example, the resistance of the circuit (*a d e f b*) is to that of (*a b*) as 100 to 1, $\frac{99}{100}$ of the current would pass by the conductor (*a b*). Now suppose a bullet, in its flight, to cut the wire (*a b*) and, passing on, subsequently to sever the wire (*d e*), it is evident that the moment (*a b*) is cut the whole current will pass through and deflect the galvanometer, and the moment (*d e*) is cut the current will cease. Now the current which will have passed through the galvanometer will, with reference to any given battery, depend first on the resistance of the circuit (*a e d f b*), and secondly, on the interval of time which may have elapsed between the severance of the two wires (*a b*) and (*d e*).

FIG. 12.



The quantity of electricity which may pass through the galvanometer will produce a momentary deflection, and that momentary deflection may be compared with the deflection obtained, all other conditions being the same, from a contact made during a known short interval of time, and, in this way, we should be able I think to measure fractions of the thousandth part of a second.

We cannot get practically a standard of electrical quantity: I suppose one could bottle up, in a Leyden jar, the unit quantity of electricity, but I do not think it would stop there very long, and, when one had got it, it would be very troublesome to work with and could only be used once: and so, even if we could obtain a standard quantity of electricity, it would be of very little use: we must, therefore, do what is actually done with liquid measure. We do not send out a pint of water as the measure of a pint, we send out a vessel capable of containing a pint: so instead of attempting to obtain a standard of electrical quantity, we propose to construct a standard of electrical capacity.

Electrical capacity.

Now what I mean by electrical capacity is this: any given Leyden jar, when its two armatures are electrified to different potentials, will contain a certain quantity of electricity. The same is perfectly true of any insulated body whatever, a sphere, a wire, or any other conductor, when these are electrified to a different potential from that of the neighbouring conductors. The quantity which any such conductor will contain depends upon various circumstances: first, it is proportional to the electromotive force used to electrify it, or, in more accurate language, it is proportional to the difference of potential between the body electrified and the surrounding conductors. In the Leyden jar, the electrified body and the surrounding conductors are represented by the inside and outside armatures, though the inside armature is generally spoken of alone as being electrified. But however highly electrified the jar may be, if the inside and outside be at the same potential and the room outside also at the same potential it, (the jar), will apparently contain nothing. Even if the inner and outer armature are at a different potential from that of the room, the inner coating will apparently contain no charge and the charge on the outer coating will be the same as

if the inner coating did not exist. The quantity which the inner armature of any given jar will contain depends, cæteris paribus, upon the difference of potential between the inside and outside armatures.

In my next lecture I propose to enter into the consideration of potential and electromotive force: for the present it will suffice for you to know, that a voltaic battery of 200 cells will produce twice the electromotive force, or difference of potential between its poles, that will be produced by a battery of 100 cells, and that a battery of 100 cells will produce one hundred fold the electromotive force of one cell, and consequently a condenser or Leyden jar, charged with one cell, has only one hundredth part of the quantity of electricity in it, which the same condenser or jar would have if charged with 100 cells. The capacity of a Leyden jar has nothing whatever to do with the electromotive force with which it is charged: but the quantity of electricity with which any given jar may be charged, depends on the electromotive force used in charging it; that is to say the same jar, charged with a battery possessed of great electromotive force between its poles, would contain a larger quantity of electricity than if it were charged with one of small electromotive force, the electromotive force of two batteries being, by Ohm's law, proportional to the current they can maintain in any one circuit of given resistance; but the larger the capacity of a jar the more electricity it will contain, with a given electromotive force acting between its armatures: for instance, the quantity contained in a small ball will be very much smaller than that contained in a large ball, when the two are electrified under precisely similar circumstances. Now the quality, in virtue of which, with a given electromotive force, different bodies are capable of receiving different quantities of electricity, is what I call, their capacity, and the capacity of a sphere, placed in the middle of a large open space is, in the absolute electrostatic measure, which I have already described, simply equal to its radius. Here we see one example of the use of choosing a sensible system of units;—in any system, the capacity of a sphere must be proportional to its radius, but in the absolute system of measurement the capacity is absolutely, speaking electrically, equal to its radius. The capacity of two large flat plates, placed parallel to each other at a small distance apart, that is to say, a distance small compared with their total area, is equal to their area divided by the distance between them. I assume that the material, surrounding the sphere, or separating the two armatures is air, because if any other insulator such as gutta percha, Indian rubber, or glass be used, the charge will be increased, in consequence of what is termed the specific inductive capacity of the insulating material.

Specific inductive capacity.

It has been found by observation that, when we substitute a sheet of gutta percha for air, between the two plates of our condenser, the capacity of that condenser is thereby increased about four fold; therefore, the specific inductive capacity of gutta percha is said to be "four," that of perfectly dry air being assumed as "one." With Indian rubber the capacity would only be increased about $2\frac{1}{2}$ fold, the specific inductive capacity of Indian rubber is therefore $2\frac{1}{2}$, and similarly glass and every

other insulator has its own specific inductive capacity. We may, therefore, say that the capacity of any system, for the reception of a statical charge or quantity of electricity, depends upon the shape and dimensions of the parts and upon the insulator used to separate the two conductors, between which induction takes place; these two conductors corresponding to the armatures of a Leyden jar or the opposed plates of a condenser.

There are various other simple forms, besides the flat plates already alluded to, the capacity of which can be calculated by pure mathematics without observation, but when we get to the more complicated shapes, such as that of the Leyden jar, or the condenser made with gutta percha, mica plates, or the ordinary submarine cable, the capacity is best ascertained by actual observation. The formula for calculating the electrostatic capacity of a submarine cable is a very simple one, viz.:

$$S = \frac{L.\ I}{2.\ \log_e \frac{D}{d}}$$

Where L = length of conductor. S = capacity in static measure. D = diameter of insulator. d = diameter of conductor. I = specific inductive capacity, referred to air. This is the case of a long cylindrical conductor, separated from an external cylinder of water, by gutta percha or some other insulator: induction takes place between the inside and outside, the inside has, therefore, a certain definite capacity for electricity, which capacity can be calculated, just as that of a sphere, from mere mathematical considerations, but it requires that the value of I, for the special insulator employed, may be known.

Unit of electrical capacity.

The unit of capacity is that which will contain the unit of quantity, when charged by the unit of electromotive force. The quantity of electricity, which can be forced into a given Leyden jar, varies as already explained with the electromotive force or, so to speak, pressure applied; electromotive force is, therefore, an essential element in the consideration of any measure of electrical capacity. The idea of this may be better understood if we suppose that, in defining the capacity of a standard pint, we described it as capable of containing so many cubic inches of air, at a given pressure, the quantity of air which we could force into it varying with the pressure employed.

Measurement of electrical capacity.

The electrical capacity of a body of unknown shape can be determined by charging it, with a given battery, and measuring the discharge of the quantity of electricity it contains, on a given galvanometer.

The following is the formula resulting from the definitions already given:

$$S = 2\ \frac{t.\ \sin \frac{1}{2}\theta}{\pi.\ R_1}$$

Where S = the capacity of the conductor, and R_1 = the resistance through which the electromotive force, used to charge the conductor, will maintain a current, producing the unit deflection on the galvan-

ometer, through which the discharge produces a deflection θ, t retains the signification given above.

The formulæ, used in the measurement of electrical capacity, are very similar to those used in the measurements of quantity; all that we require to do is to note the time of oscillation of the needle of our galvanometer, and the total resistance of the circuit in which the electromotive force, charging the condenser, of which we wish to ascertain the capacity, would produce the unit deflection upon that particular galvanometer. If we wish to measure the capacity of a given submarine cable, we observe first how many times in a minute the needle of the galvanometer, which we propose to use, swings or oscillates freely; we next take the battery, with which we intend to charge our cable, and pass the current through our galvanometer, adding resistance to our circuit till, probably with the help of a shunt, we obtain the unit deflection, or such an observation as will enable us to calculate what amount of resistance we must add to our circuit in order to obtain the unit deflection on that particular instrument: thus we may observe that the battery gives a deflection of 250 divisions on a reflecting galvanometer having a resistance of 4000 units, with 999 parts of the current shunted away from the galvanometer, 10,000 units of resistance added by resistance coils and a resistance in the battery of 400 units. The resistance of our circuit in this case would be 10,404,000 units for a deflection of 250 divisions, without a shunt, and R_1 would therefore be $250 \times 10{,}404{,}000 = 2{,}601{,}000{,}000$. We next charge our cable, with the same battery, and discharge it through the galvanometer, noting the deflection, and we then have all the elements for calculating the capacity of that particular length of submarine cable. The capacity of any given Leyden jar, or of a condenser, used for firing fuzes, of any particular form may be found in a similar manner, and this method of measuring various capacities admits of many other useful applications. Capacities can, of course, be simply compared, by measuring the quantities which a given battery, or other electromoter, will produce in them. Thus all the methods, which I have given you for comparison of quantities, serve also to compare capacities. Capacities can be measured either in the Electrostatic or the Electro-magnetic measure, given in my first lecture on Electrical measurements: if the resistances, employed in the experiment last described, were in Electrostatic measure, the capacity found would be in electrostatic measure, if in electro-magnetic measure it would also be in electro-magnetic measure, and there is a simple constant, which gives the value of the ratio, between these two measures.

Comparison of electrical capacities.

I will now describe to you a totally different way in which capacities, as well as quantities, can be measured or rather compared. Let us suppose that we have two Leyden jars and that we wish to know whether they are equal. If we charge one of them positively and the other negatively, with exactly similar electromotive force, and then join them by a conductor, the positive electricity in the one, should exactly neutralize the negative electricity in the other, and the com-

bined system should be completely devoid of all electricity whatever. If we connect the centre of any given battery with the earth, if the battery is symmetrical and well insulated, we shall have exactly equal electromotive force from its two extremities, positive at one end and negative at the other: now if we charge one condenser with the positive pole and the other with the negative and subsequently join the two together we can ascertain, by a simple discharge through a galvanometer, whether any electricity remains. If we have a surplus of positive electricity the galvanometer will be deflected in one direction, if of negative in the other direction, and it is a very simple matter to ascertain in which direction a positive or negative charge will deflect any given galvanometer; if we have a surplus of positive electricity we know that the jar, which had been charged from the positive pole of the battery, is of greatest capacity, and if the surplus is negative, that charged from the negative pole is of greatest capacity. If, after connecting the two charged jars, there is no discharge whatever from the system, they must be of exactly equal capacity. This you see is a completely new method of comparing quantities of electricity, quite distinct from those which I have previously alluded to. The application to this simple case, illustrates the principle by which the more delicate arrangements, actually used in practice, are governed and I shall now proceed to show you how, by a precisely similar proceeding, we are enabled to ascertain the ratio between the capacities of any two given condensers.

Fig. 13.

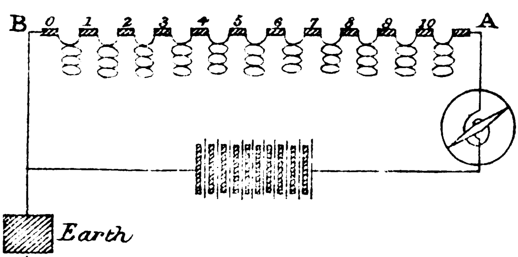
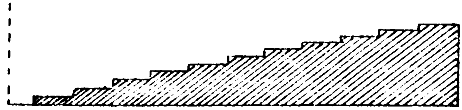


Fig 14.

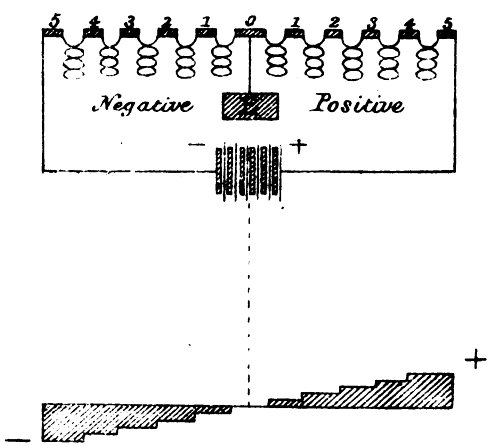


Instruments used for measurement of Potential.

If the two poles of a battery, as in Fig. 13, be joined by a long set of perfectly equal resistance coils, the current passes from the positive pole of the battery through each of these coils in succession. If the total resistance of this whole system of coils is very great, as compared with that of the battery, it may be so arranged that, at the point A, we shall have a very high potential, nearly the full power of the battery, which will gradually diminish, to the point B, where we shall have zero potential, by which is meant the potential as compared with that of the earth. At each terminal, between each coil, the electromotive force would be diminished, from an amount which we may call 100, first to 90, then to 80, 70, 60 and so on to nothing, so that we can choose, at a known point, the exact potential that we may require. In Fig. 14, the stepped line corresponds to a gradual fall of potential at each terminal, the height of the step above the base line being proportional to the potential at the corresponding terminal.

We have here before us an instrument made on precisely this principle not, as in Fig. 13, with 10 resistance coils but with 100, and by means of a slide moveable along it, we can connect any condenser with any one of the small brass plates,—each separated by their intervening resistance coils, and thus charge this condenser with any required fraction of the total electromotive force of the battery we may be using: if we now suppose the arrangement in Fig. 13 to be doubled, as in Fig. 15, we shall obtain, on one side of zero a gradually increasing series of steps, so to speak, of positive electricity and, in the other direction, a precisely similar series of steps of negative electricity, and we may then discover by experiment, the exact ratio, of the positive and negative potential, with which we must charge any two condensers, to be compared, in order that the two

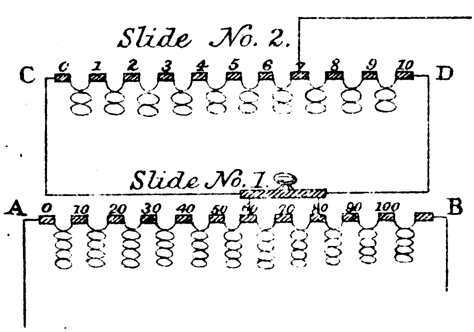
FIG. 15.



charges, one of positive and the other of negative electricity, shall precisely neutralize each other. If one condenser is so large as to require a positive potential of only one, and the other so small as to take a negative potential of ten in order that, when the two are joined together, there may be no sensible electricity, no sensible difference of potential between them, we may conclude that one condenser possesses exactly ten times the electrical capacity of the other.

An idea of the practical use of this arrangement, for producing any variety of potentials required, is given by the fact that it is precisely that which was actually used on board the Great Eastern, and at Valentia, during the process of laying the last Atlantic cable. These divisions into 100 parts were not, however, found sufficiently minute. In Fig. 16, we have an arrangement, an additional set of resistance coils, C D, so connected with the first set, A B, that the potential of any one coil of the first set may be again divided into tenths. The combination used in connection with the Atlantic Cable was much more minute; by means of a second arrangement of 100 resistance coils, connected with brass plates and placed as, C D, with a moveable slide, bridging two coils in A B, which also contained 100 coils, each having a tenfold greater resistance than those between C D, a means was afforded of dividing the potential, of any one of the main 100 coils, AB, again into 100 parts, so that finally the potential could be taken off at a series of points, each differing by $\frac{1}{10000}$ from its neighbours : so that any potential required, from zero up to 10,000, could be chosen and connected at will with the combination employed for the several tests used.

Fig. 16.



With such a combination as that described, we can measure the capacity of any two condensers to $\frac{1}{1000}$, provided the battery employed is sufficiently strong that, after the connection between them has been made, any residual electricity left may be sufficient to deflect a galvanometer; and galvanometers can now be made so sensitive, that they will always show a quantity however small.

I hope, in my next lecture, to be able to show you another method of ascertaining whether any electrical residuum does remain, when we employ this process in the comparison of capacities, and also whether that residuum is positive or negative.

LECTURE IV.

ON

ELECTRICAL MEASUREMENTS,

DELIVERED BY

FLEEMING JENKIN, ESQ., F.R.S.,

At the Royal Engineer Establishment, Chatham, on the 28th February, 1867.

WRITTEN BY

CAPTAIN R. H. STOTHERD, R.E.,

AND CORRECTED BY THE LECTURER.

In my present lecture, I propose to treat of the measurement and comparison of various electromotive forces, which may be otherwise described as due to a difference of potential and, in conclusion, to enumerate some of the tests which were actually applied on the Atlantic Cable, and afford illustrations of the practical application of the various theories, which I have brought under your notice in these lectures.

Definition of the term Potential.

In my first lecture, I mentioned that the electromotive force between two points, in a conductor or in space, is proportional to the amount of work which a certain quantity of electricity would do, in passing from one point to the other. This is true whether the electromotive force be due to a voltaic arrangement, such as a battery, or to a current produced in any way, or to statical charges of electricity distributed in any manner whatever; there being no essential distinction between electromotive force or difference of potential, due to any of those causes or to all combined. But before going back to this rather complicated idea, I should like to show you practically what I mean by electromotive force, and also by difference of potential, and I will, for this purpose, again refer to my old analogy of water forced through pipes. Electromotive force, as affecting a current of electricity, may be compared to a head of water, tending to produce a current of water through pipes. Electromotive force, is dependent on, what I have

called, the difference of potential: we can get no force whatever tending to produce a current, between two points in a given wire or between two points in space, unless those two points are in different electrical conditions, and it is that difference of condition which I mean by difference of potential. As no current of water could exist between two points in a given pipe if those points were at the same level, and it would require a difference of level to produce the head or pressure necessary to send the water through, so electromotive force, tending to produce a current, may be considered as exactly equivalent to a head of water, while difference of potential is analagous to the difference of level, to which that head is due. The difference of level might be defined as the difference of potential of gravitation; for you will observe that we might measure the difference of level between two points in this room, for instance, by measuring the amount of work which a weight would perform in falling through the space, between the upper and lower level of the points referred to. So that, substituting the unit of mass for the unit quantity of electricity, we find that the definition of difference of potential applies to gravitation as well as to electrical attraction, and is equivalent to a difference of level so long as the work, done by a falling weight, can be taken as proportional to a difference of level. The measurement of work would of course be a round-about way of levelling, but it could so be done. Similarly we could measure the difference of electrical level, or potential, by measuring the amount of work a certain quantity of electricity would perform, in passing from one point to another, but this would also be a round-about way of arriving at the required result. Just as there are more direct methods of making mechanical measurements, so there are more direct methods of measuring differences of potential, as I hope presently to show you.

Production of electromotive force or difference of Potential.

Electromotive force, or difference of potential, may be produced in a great many different ways, as for example by a voltaic battery, between the poles of which an electromotive force or given difference of potential exists. Again, if I rub a piece of sealing wax I produce a difference of potential between it and the surrounding objects. If I rub a piece of glass I produce a greater effect than occurs with the sealing wax but in an opposite direction, that is to say if I call the change produced by rubbing one material raising the potential of surrounding substances, I must call the change produced by rubbing the other lowering it. Again electromotive force, or difference of potential, may be produced by magnetic induction, as, for instance, by moving an armature or keeper in the vicinity of a permanent magnet: and there are various other arrangements, such as the motion of a wire conveying a current, by which electromotive force or difference of potential may be produced.

Under certain conditions electromotive force is produced in such a manner as to be capable of maintaining a permanent current, for example, if we join the poles of a voltaic battery, by a metallic conductor, a current circulates but the difference of potential is permanently main-

tained between those two poles. On the other hand, electromotive force may be due to causes incapable of maintaining a current even for a very short time. Thus if we rub a stick of sealing wax it assumes a certain electrical condition, with reference to all objects in its immediate vicinity, and this condition is described by saying that its potential differs from theirs. A unit quantity of electricity would, in passing through the air from the electrified stick of sealing wax to any given object, experience a certain amount of resistance, or a certain attraction, and must either receive, or perform a certain amount of work in passing from one point to the other, but in this case if the two points, thus proved to be at different potentials, were joined by a wire no permanent current would be established, but the two points would be immediately brought to a uniform potential. The words difference of potential are applied with equal accuracy to both cases, but are somewhat more generally used to express the difference of electrical condition between various points, as produced by the neighbourhood of an electrified body, and electromotive force is more generally used to express a difference of potential capable of maintaining a current; but the two phrases are interchangeable and what measures electromotive force, measures a difference of potential and vice versa.

Potential of the earth assumed to be Zero.

In speaking of the potential of a body its difference of potential, from that of the earth, is meant, the earth being taken to represent a body which is not electrified at all, or the potential of which is assumed to be zero. When we speak of the potential of an electrified piece of sealing wax, it means the difference between its potential and that of the earth.

Gold leaf Electroscope.

When a body is charged to a high potential it is popularly said to be highly electrified, and the degree of electrification is roughly indicated by a certain class of instruments called electroscopes. If we charge a gold leaf electroscope, (one of the simplest and oldest forms of this instrument), by touching it with any electrified body, the gold leaves diverge and we may get a rough idea of how highly it is electrified or, in other words, to how high a potential it is charged, by the amount of divergence of those leaves. The popular explanation of this divergence of the leaves is that, being charged with the same kind of electricity, they mutually repel each other; but, strictly speaking, the divergence is caused by the difference of potential between the gold leaves within the glass and the surrounding objects outside it: if I approach my hand to one side of an electroscope of this nature, after the latter has been charged, the gold leaf, which had previously remained perfectly steady, is attracted towards it: if I move my hand round to the other side the gold leaf moves round, in the opposite direction towards it, again if the gold leaves were surrounded by a conductor electrified to the same potential as themselves, they would not diverge at all, thus showing that the divergence of the leaves is really due to a difference of potential, as above stated, from that of surrounding objects.

The gold leaf electroscope is a very rude instrument and shows so

Peltier's Electroscope or Electrometer.

imperfectly what is required, that it can only be used as a means of elementary illustration. Another instrument, called Peltier's electroscope, is an improvement on the gold leaf combination: by it the presence of a certain quantity of electricity or, in other words, of a certain charge is indicated; it also gives an imperfect indication of the potential of a charge, the deflection of a given needle being greater, cæteris paribus, when the instrument is charged to a high, than when it is at a low potential. The construction of this instrument, (Peltier's electrometer), is well known: if we charge the insulated ball and index with electricity, the needle is deflected from the small permanent metallic bar running across the instrument, for the same reason that the two gold leaves are repelled from one another. Though a better instrument than the gold leaf electroscope, it is nevertheless far from being perfect, and ought, properly speaking, to be called an electroscope, and not an electrometer. The needle is very much acted on by bodies in the immediate neighbourhood, and the indications of the instrument thus deranged: this is very easily exemplified, for if I put my hand near the outside of the instrument, when the latter is charged, the needle is attracted towards it just as the gold leaf was. Again this instrument requires a very considerable charge before it indicates anything. In order to produce, by battery power, a result, (such a deflection of the needle as that caused by a charge of frictional electricity), it would be necessary to use a Voltaic battery of from 200 to 300 cells: with such a battery we should, if the instrument were in good order, and the needle well balanced and its directing magnetism not too strong, obtain a deflection of the same kind as that produced by a charge of frictional electricity, by simply connecting one pole of the battery with the ball attached to the upright brass arm and index, the other pole being connected to the earth, and thus to the conductors in the neighbourhood of the index. You will remark that the deflection is not caused by the passage of a current, as in the galvanometer, but is due to the attraction caused by the difference of potential between the index and the surrounding bodies, so that the effect is due to what is commonly called statical electricity, whether produced by a battery or by friction. Thus it is sufficient to touch the ball of the electroscope, for an instant, with the wire from the battery which may be at once withdrawn, and the charge then continues to keep the needle deflected, till it gradually passes away by leakage, or is suddenly removed by touching the ball with any conductor through which it is conveyed.

The Peltier electrometer might be arranged with an arc, graduated so as to indicate the relative potentials of electrified bodies touching the ball on the upright brass arm. Simple graduation into degrees would be insufficient for this purpose, for the deflections increase in a much smaller ratio than the potentials producing them, and moreover according to no definite law. It would also be necessary to screen the inner system by a metal case from irregular action due to neighbouring bodies.

The potential of any metallic body or good conductor, through which no current is passing, whatever may be its shape, is the same throughout the whole of that body. If, for example, I charge a brass ball, with electricity, that charge at once establishes itself in a state of equilibrium, so to speak, over the whole ball and if any two points on it were joined by a wire no current would pass along that wire. Again, if I hold a second brass ball in the vicinity of that which I have already charged, I shall have a certain quantity of positive electricity on one side of each ball and a certain quantity of negative electricity on the other side of the same balls, but every point of each ball will be at one and the same potential; no work is done in moving the electricity round or through each ball, nor is it in such a state as to produce a current from one side to the other. A consideration of this fact serves to illustrate more fully the meaning of the word "potential," as compared with the common phrases "high charge" and "intensity."

Potential throughout a given charged body the same.

You observe that one part of the metallic body may be correctly described as charged with negative electricity, the other part with positive electricity, and yet these two parts may be at one and the same potential. Thus all parts of the charged and insulated system of the Peltier electroscope are at the same potential, though the charge may be very unevenly distributed among the parts.

Again the word "tension" is sometimes erroneously used instead of "potential." Tension is frequently conceived as that property in virtue of which electricity is ready to jump across a small intervening space of air, indicating its presence by a spark. If this description of tension were correct, the tension at the end of a pointed rod would be greater than that of a ball connected with it, contrary to our definition. In reality the potential, at the end of the pointed body, would be the same as that on any part of the ball or rod, though the quantity of electricity, accumulated in the one, would not be the same as that developed in the other, nor would the pressure against the air nor the quantity of electricity accumulated at the two places be equal.

Potential differs from tension, intensity, high charge, &c.

I hope I have thus made clear to you that the word "potential" has a certain definite meaning, and must not be confounded with the terms "tension," "intensity," "high charge," &c., which so often occur.

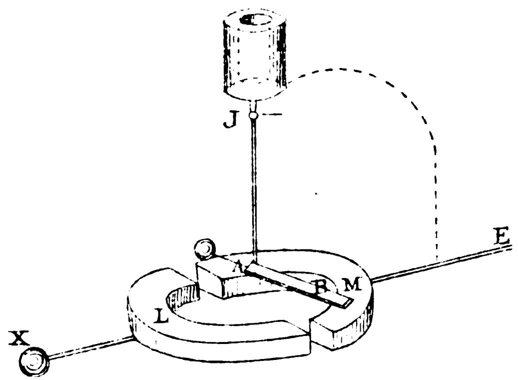
By some writers the word tension is however used in the same sense as potential.

I will now introduce to your notice an instrument, of very recent construction, by means of which we can detect and directly measure differences of potential. Fig. 17 is a diagram illustrating the principle of this instrument, in it A B represents a very light body, (usually a very light needle of aluminium), suspended by a very fine platinum wire, A J, which gives it a small, but only a very small, directing force. This wire, A J, is in connection with the inside of a Leyden jar, composed of very highly insulating glass, and in the construction of which special precautions are taken, so that it may hold its charge for a very long time. Now suppose that a considerable charge of elec-

The modern form of electrometer.

tricity is given to this Leyden jar, by which its internal armature and consequently the needle A B, in connection with it, is raised to a very high potential, this needle will be attracted by or repelled from any neighbouring body, differing from or similar to it in potential. Referring to Fig. 17, we see two equal portions of a metallic ring, L and M,

Fig. 17.



completely insulated from each other; when these two portions are in the same electrical condition it is evident that the needle, being equally attracted to, or repelled from both, will remain stationary, if, on the contrary, we charge one positively, leaving the other in connection with the earth, the needle, if negatively electrified, will be attracted towards the positively charged plate, or if this plate be negatively charged it will repel the needle; and this will be true whenever the one plate is more positively or more negatively electrified than its neighbour, even though this neighbour be not in connection with the earth; or though both plates may be negative or both positive as compared with the earth. In stricter language, the needle will be attracted in one direction or the other whenever the two plates, L and M, are at different potentials; the direction of the attraction will depend on which plate is at the higher potential and the force of the attraction will be, cæteris paribus, proportional to the difference of potential between the plates, but will be greater the higher the potential of A B.

In fact the instrument is constructed on the principle, so simply illustrated, in the well known experiment, in which two pith balls are made to attract or repel each other, when charged with electricity of opposite, or the same sign.

The object of the Leyden jar is to keep the little needle at an extremely high electrical potential, and so to increase the force, with which the small differences of potential in the two plates, M and L, attract, or repel the needle, under which circumstances minute differences of potential cause great deflections and the instrument is astonishingly sensitive.

The action of the Leyden jar is simply to diminish the effect of the necessary leakage, or loss of the electricity, by which the needle is charged to a high potential. The needle could, of course, be equally highly charged without the presence of the Leyden jar, but the charge would then be much smaller in quantity though equal in potential, and a very small loss would thus reduce the potential greatly; but a small loss from a large quantity in the jar has little effect on the potential. Thus a very small leakage from a small standpipe of water would reduce the head considerably, but the same leakage from a large standpipe, or from the same small standpipe leading from a large reservoir, would not sensibly affect the head of water. It is as easy to insulate the whole armature of the Leyden jar, as the simple insulated needle, and the jar gives us a precisely analagous advantage to that of the large reservoir of water.

The reflecting electrometer.

In connection with the needle, in instruments of this nature, is a small mirror arranged, in a similar manner to that in the Reflecting galvanometer, to move with it and, by the motion of a spot of light, to indicate very minute deflections on a graduated scale; there are two metallic conducting wires, shown in Fig. 17, at E and X, in connection with the two sections, L and M, of the ring, by which they may be charged. There is also a wire, in connection with the Leyden jar, by which the instrument can be charged and, when once charged, it will remain in that condition, owing to care in the selection, cleansing and drying of the glass used to insulate it, for days or even weeks if necessary. If we rub a piece of sealing wax and touch one of the conducting wires, E or X, the needle will be deflected and its deflection will be indicated by the motion of the spot of light, reflected by the mirror in connection with it, in one direction. Again, if we rub a piece of glass and touch the same conducting wire, the semi-ring in connection with it will be charged with electricity of an opposite character to that produced by the sealing wax, and the needle will be attracted, and consequently the spot of light will move in the opposite direction. In fact the instrument is affected, by a static charge, in the same way as the rougher electroscopes already described, but it distinguishes a positive from a negative charge and is infinitely more sensitive: for example, a deflection of 100 divisions is produced on it, by placing the two poles of a single Daniell's cell for an instant in connection with the two wires E and X; with three or more cells a pro-

portionately greater deflection is produced. In using this instrument, in connection with a battery, it must be distinctly borne in mind that the deflection of the needle is not, as in the case of the galvanometer, due to a continuous current of electricity but merely to the charge or, in other words, the difference of potential between the semi-rings: this is easily shown by charging the instrument and then removing the battery connections, when the needle will remain deflected and not, as in the galvanometer, return to zero; if both terminals are simultaneously touched by a conductor, such as my hands, the difference of potential between them will be removed and the needle will return to zero. If the poles of the battery be reversed, the needle will be deflected in the opposite direction. The instrument does not indicate the amount to which the two semi-rings are electrified, but shows the difference of potential between them. They might both be at a very high potential but no deflection would be observed if they were at the same potential. The plates, L and M, and the moveable needle must all be enclosed in a metal case, or induction from neighbouring bodies would disturb the indications. The deflections of the instrument not only increase with an increased difference of potential between the plates, but are truly proportional to that difference, so that this instrument, invented by Sir William Thomson, is a true measuring instrument; an electrometer not an electroscope.

Reflecting electrometer indicates a difference of potential with extreme accuracy.

I explained to you on a former occasion, how a graduated difference of potential could be produced by the interposition of the ordinary resistance coils: I also explained how, between two poles of a voltaic battery, the potential of one pole of a battery would gradually diminish to zero, if that pole were connected to the second pole, which was itself connected to earth, and also that between any two points in the wire, connecting the poles of a battery, we have a difference of potential as well as between the two poles or terminals. This difference of potential would be a difficult thing actually to show, if the conductor joining the two poles were a very short piece of wire, but can easily be made evident, on the electrometer just described, when we interpose a long wire, arranged in the form of resistance coils. As we have only the means of touching these coils at their terminals, the effect produced by them is exhibited in diagram Fig. 14, where the vertical ordinates represent the differences of potential and the horizontal ones the corresponding resistances, the whole assuming the form of a series of steps, commencing from the maximum of potential and gradually diminishing down to zero. If we connect one pole of a battery, of say 30 Daniell's cells, to the terminal of a box of resistance coils, the other pole of the battery and the other terminal of the set of resistance coils being connected with the earth, we have, at the terminal attached to the battery, the maximum potential due to a battery of 30 cells, while, at the terminal fixed to the extremity of each single coil, that potential will be found to have diminished, as represented by the series of steps in the diagram Fig. 14, till, at the terminal of the box of coils, to which the earth connection is attached, the potential becomes zero: also the

difference in potential between any two points in these coils will be directly in proportion to the number of small steps or, in other words, of equal coils between them.

Effect of resistance coils in connection with reflecting electrometer.

The effect of these resistance coils is shown, by connecting one terminal of the electrometer with a slide, which can be moved along the terminals attached to the single coils, while the other terminal of the electrometer is in connection with earth; the deflection, indicated by the spot of light, will then increase as the slide is moved away from the end in connection with earth, and will be in simple direct proportion to the number of terminals, intervening between the slide and the earth terminal, and the position of the spot of light on the scale will be altered accordingly. Thus when our slide is on the first terminal, there being a hundred coils and 30 cells, we get a deflection of 30 divisions, corresponding to a difference of potential due to $\frac{1}{3}$ of a cell. When the slide is on the third terminal, we have a deflection of 90 divisions, such as would be produced by a single cell.

Uses to which reflecting electrometer may be applied.

The uses to which this very sensitive form of electrometer may be applied are very numerous indeed. It may be used, in the same manner as the ordinary Peltier's electrometer, in testing the insulation of a submarine cable, but whereas with Peltier's instrument it is necessary to use frictional electricity or a very large number of cells of a battery, with the chance of damaging the cable, with this instrument we can test insulation very well using only 5 or 6 cells, in a precisely similar manner, the deflection of the spot of light indicating, as before, the relative charges remaining in the cable after the lapse of various periods of time. Another use to which this instrument may be applied is for meterological observations: to ascertain the electrical condition of the atmosphere, which is sometimes charged positively and sometimes negatively. If we place a burning match in connection with one of the poles of the instrument, the hot air being a conductor, the semi-ring in connection with it is gradually brought into the same electrical condition as the air in its immediate neighbourhood. (A jet of water will answer the purpose in a similar manner to the lighted match.) To illustrate this application of the instrument it is only necessary to electrify the air in its immediate neighbourhood, with a common electrical machine, when the spot of light will be seen to be permanently deflected to one side as that electrical machine is approached, without actual contact, to the terminal bearing the match. This instrument is also useful for ascertaining the potential of any given battery, or of a cable through which signals are passing, under given circumstances, as well as for several other experiments of a similar nature.

The resistance of any insulating material, even of very short length, may also be determined by this instrument, by noting the loss of charge, as indicated by it and required in the following formula. Let a body such as the conductor of a cable, of known capacity S, be charged to a given potential P, and let it be gradually discharged through the conductor of great resistance *r*, such as the insulating sheath of a sub-

marine cable; let the time t, at the end of which the potential of the body has fallen to p, be noted, then we have

$$r = \frac{t}{S. \log_e \frac{P}{p}},$$

where r is the resistance required, in electrostatic absolute measure, if S is in electrostatic measure; or r would be in electro-magnetic measure, if S were in electro-magnetic measure. To reduce r in the latter case to Ohm's, divide it by 10,000,000. The ratio $\frac{P}{p}$ is obtained by observations on the electrometer.

Points to be attended to in making and using the reflecting electrometer.

The chief difficulty in the management of this instrument is to ensure the Leyden jar holding its charge properly. With this view it is necessary that it should be made of carefully selected glass, which contains no metallic substance whatever in its composition, the inside must be most carefully washed with distilled water and dried, not with a towel or anything likely to produce the very slightest suspicion of fibrous residuum, but by holding it to the fire: a little pumice stone and perfectly pure non-fuming sulphuric acid is then put in it, and it is ready for use. A jar prepared in this way will hold its charge for as much as six weeks at a time.

Portable reflecting electrometer.

I will now, for a moment, call your attention to a small and very portable instrument of this nature, made on similar principles to the larger and very sensitive one with which I have been experimenting. It is so small and light as to be easily carried in the hand, and it requires 4 or 5 Daniell's cells to produce any mensurable effect on it: nevertheless it is sufficiently sensitive to measure atmospheric electrical phenomena with considerable accuracy. These two very beautiful and delicate instruments are recent inventions of Professor Sir W. Thomson, of Glasgow, and were made under his superintendence.

Reflecting electrometer, as at present made, does not measure differences of potential in absolute units.

I have now concluded all I had to say concerning the *comparison* of various electromotive forces or differences of potential. We have not yet got instruments by which we can measure differences of potential directly, in those absolute units which I have described to you. Where currents exists we may obtain that measurement by indirect means: as for example, if we know the current and the resistance of a circuit, through which it is passing, we may deduce the electromotive force between any two parts of the circuit, from Ohm's law. Thus we obtain indirect measurements of electromotive force or difference of potential but no instrument has yet been made, by which direct measurements of difference of potential, in absolute units, can be made as I have shown you can be done for currents and resistances: in order to attain such an object, the instrument, which I have just described to you, must be so far improved that we may obtain at all times exactly the same deflection with the same difference of potential, which has not yet been done, though it is to be hoped that this very desirable end may, in the course of a few years, be attained.

I will now describe to you one of the most important applications of the various measurements, which I have brought to your notice in my present and previous lectures, viz., tests during the laying of the Atlantic cable: almost every one of the measurements described were made use of in that very important undertaking. Diagram Fig. 18 represents the arrangements which were used on shore at Valentia, and Fig. 19 those which were used on board the Great Eastern, on that occasion. In the former, (Fig. 18), the end of the cable is shown at S, attached to a switch by which it could, at will, be connected with either of the three terminals, (numbered 1, 2, and 3), in diagram: it was usually connected with number 1. From the point S there was also a permanent metallic connection to what is here called Smith's resistance and thence, through the galvanometer G, to earth. Smith's resistance was not a metallic resistance, like a resistance coil, but was composed of a substance having a very high resisting power, in fact almost, though not quite, sufficient to insulate the end of the cable. Now when a permanent current was sent from the ship to the shore, the extremity of the cable at S, being almost perfectly insulated, was raised to a very high potential and a very feeble current was produced, through this resistance (Smith's), which was indicated upon the galvanometer G. You will perceive that, if the cable had been broken, no current could possibly have arrived and the galvanometer would have ceased to be deflected or, if the cable had been injured so as to allow any portion of the current to leak away, through what is usually designated a fault, the potential at S would have been lowered and the current, passing through Smith's resistance, would have been diminished, as would consequently have been the deflection on the galvanometer. By this means the people on shore had always before them an indication of the state of insulation of the cable and, had it suddenly been broken or even damaged, that break or damage would have been instantly indicated on the galvanometer G.

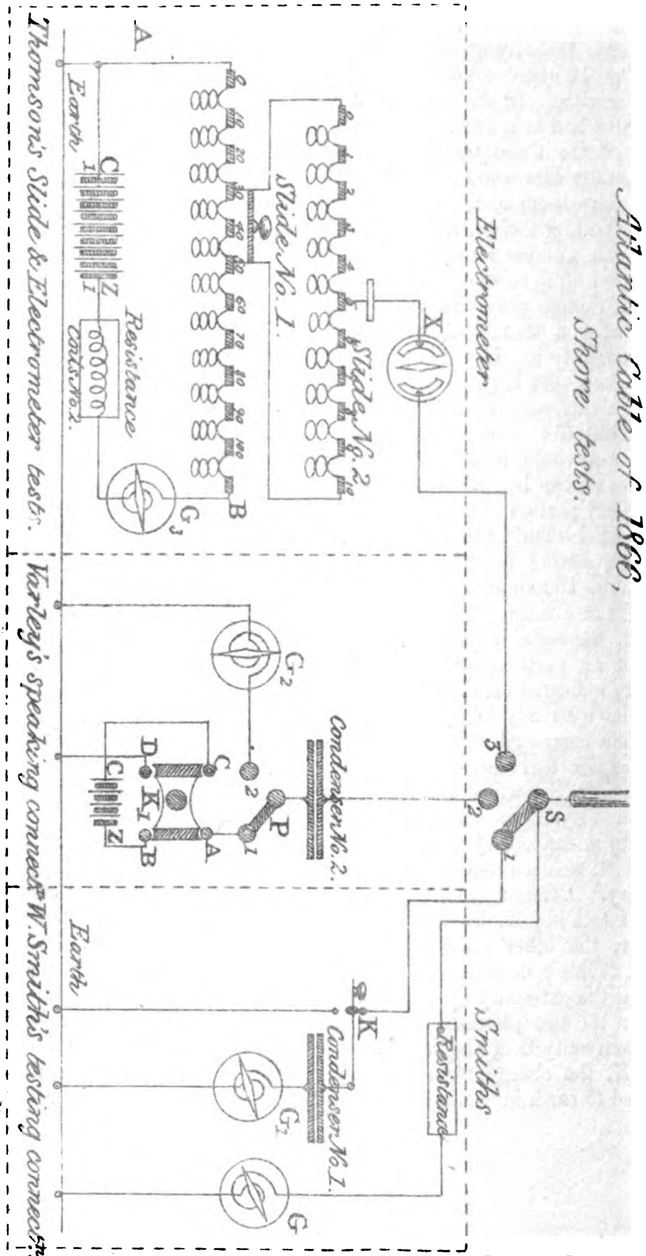
Application of tests in laying Atlantic Cable.

Smith's resistance.

I have already told you that Smith's resistance was not a metallic one, but composed of a substance the resistance of which might alter; it was for this and other reasons deemed necessary to introduce a second test, by which the people on shore could ascertain whether the ship was sending a current, whether they, (the ship), had got a given battery in connection with the cable and whether the potential, at the point S, was maintained as high as it ought to have been with that battery. Referring to Fig. 18, you will perceive a line from terminal No. 1 to a key K, usually in connection with one plate of condenser No. 1, the other plate of which was connected to earth: the upper plate of this condenser was, therefore, always charged to the same potential as the extremity S of the cable, and the difference in potential between the two plates of the condenser would be equal to that between the extremity S of the cable and the earth. By the depression of the key K, the charge from the upper plate of the condenser would be passed to earth indicating, by the deflection produced on the galvano-

Second means of ascertaining Potential.

Fig. 18.


Atlantic Cable of 1866,
Shore tests.
Electrometer
Slide No. 1
Slide No. 2
Resistance
coils No. 2
Earth
Condenser No. 2
Condenser No. 1
Resistance
Smiths
Earth
Thomson's Slide & Electrometer tests.
Varley's speaking connecⁿ
W. Smith's testing connecⁿˢ

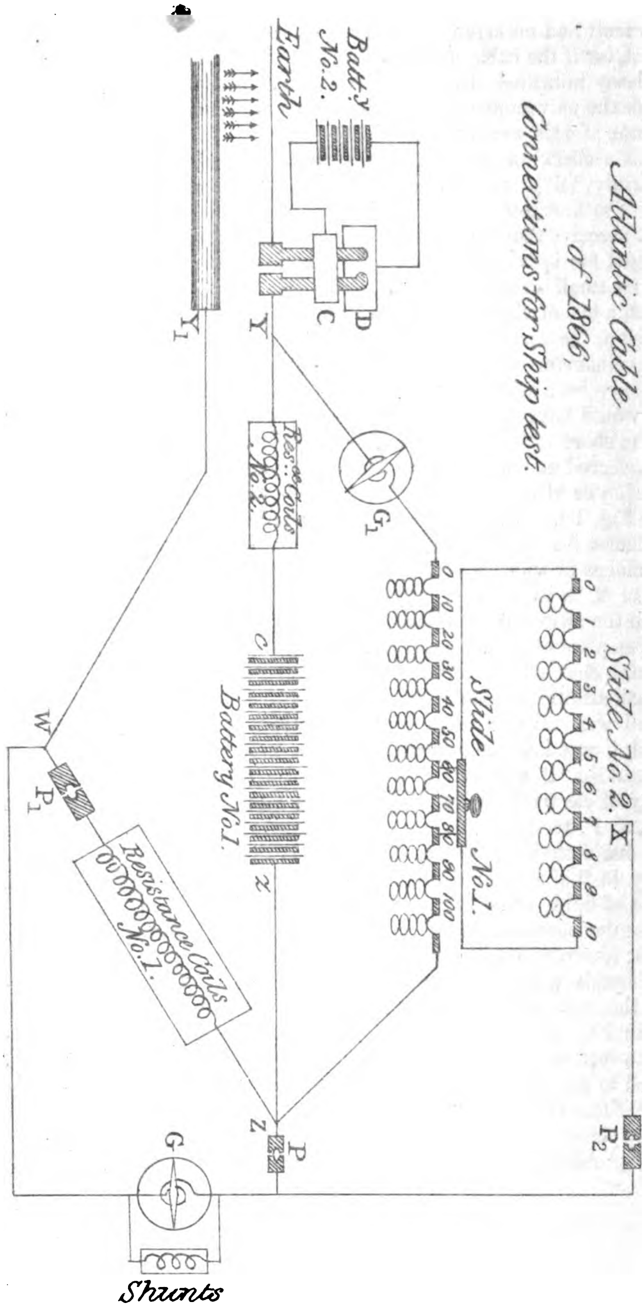
meter G_1, in connection with the lower plate, the potential of the extremity S of the cable.

If therefore any change had been made in the battery on board ship, or if a fault had occurred in the cable, by which the potential had been lowered, or if the cable had been broken, these things would one or all have been indicated, by the alteration or cessation of the discharge through the galvanometer G_1. No further information was obtainable by means of this second test than by the first, but the second test acted as a check on the first, a check rendered important owing to the uncertainty, felt by some, as to the constancy of the resistance, (Smith's), used in the first test.

Mode of signalling from shore to ship and vice versa.

You perceive that this second testing arrangement could easily have been used for speaking purposes, since every time the key K was depressed a small charge, a small bottle full of electricity so to speak, was taken out of the cable and was again supplied by the battery on board ship, the current from which, rushing in, would be indicated by the galvanometer on board ship and the deflections, thus produced, might have been arranged to represent an alphabet or code of signals, which would have afforded the means of communicating very readily from the shore to the ship. A different mode of signalling was however preferred and when it was desired to communicate, from the shore to the ship or vice versâ, the switch at S was passed over to terminal No. 2, Fig. 18. This terminal was in connection with the upper plate of condenser No. 2, the lower plate of which was provided with a switch P, by means of which it could be connected with either of the terminals, Nos. 1 or 2, in its vicinity. When a message was to be received from the ship the switch P was placed in connection with terminal No. 2; the upper plate of condenser No. 2, being in direct connection with the cable, was charged to exactly the same potential as the cable, and when any small additional charge was added to that cable on board ship, its potential was raised: when on the contrary a small charge was abstracted, it was lowered: in this way, by induction, the lower plate of condenser No. 2 was alternately charged with a greater and smaller quantity of electricity and, being in connection with the earth, through the switch P, terminal No. 2 and the galvonometer G_2, the current, first in one direction and then in the other, due to the alteration of the quantity in the induced charge, would be indicated by this latter, and the spot of light, being in this manner deflected in one direction or the other, as the potential of the upper plate of the condenser No. 2 was raised or lowered at will, by the people in the ship, an intelligible system of signals was easily transmitted. The mode in which the potential of the cable was raised or lowered by the people on board ship is shown in Fig. 19: by means of a couple of reversing keys, in connection with battery No. 2, the electromotive force of that battery, could be added to or subtracted from that of battery No. 1 at will, increasing or diminishing the potential of the cable, according as the second battery was placed in opposition to, or in conjunction with the first. The two keys, shown in diagram, were made to act simply, like those of

Fig. 19.


Atlantic Cable of 1866,
Connections for Ship test.
Slide No. 2.
Slide No. 1.
Batty. No. 2.
Earth
Res. Coils No. 2.
Battery No. 1.
Resistance Coils No. 1.
Shunts
G
G1
P
P1
P2
W
X
Y
Y1
Z
C
D

some patterns of the single needle instrument, between two metal plates C and D, one connected to the positive and the other to the negative pole of battery No. 2, the extremities of the keys being connected, one to the cable and the other to earth, and it is easily seen how, by simple depression of one, or the other, the positive or negative poles of the battery No. 2 could be so joined with battery No. 1, as to raise, or lower the potential produced on the cable by the latter battery.

When the people on shore wished to speak to the ship they moved the switch P, (Fig. 18), from terminal No. 2 to terminal No. 1, and used the small battery C Z in connection with the reversing key K_1, to charge the lower plate of the condenser No. 2 positively or negatively, and thus raise or lower its potential and, by induction, to act on that of the cable at will. The effect in this case would be, to abstract a portion of the charge and distribute it on the upper plate of the condenser, causing a slight rush into the cable from the battery on board ship, when the positive pole of the battery C Z was placed in connection with the lower plate of the condenser No. 2 and, when the negative pole was connected with it, to drive back the charge from the condenser into the cable ; either of these effects would be apparent on a galvanometer on board the ship, and the right and left deflections, by which the usual system of signals is transmitted, would be, as before, obtained at will. The reversing key K_1, is shown differently in the diagram from that already described as used on board ship, but its principles of construction and action are precisely the same, the object being to bring the positive or negative pole of the battery C Z in connection with the lower plate of the condenser No. 2 at will, and to put the opposite pole of the battery to earth.

Extremity of Cable still remained insulated when messages were in course of transmission.

You will perceive, by a reference to the diagram Fig. 18, that when messages were in the act of being transmitted from shore to ship, or vice versâ, the extremity of the cable S was still kept insulated by the upper plate of the condenser, so that there was no direct circuit through the earth. The galvanometers, both on shore and on board the ship, were affected solely by induction, between the plates of condenser No. 2, as already described. In virtue of this arrangement, no portion of the charge of the cable was ever permanently withdrawn, and no succession of signals could produce an effect at all analagous to loss, or leakage through a fault, as might have been the case had the first named arrangement for speaking been used, viz., that connected with terminal No. 1 of switch S.

Mode of regulating potential of battery.

Referring again to Fig. 18, you will perceive a terminal marked No. 3, to which the extremity S of the cable was, from time to time, attached by means of the switch. This terminal was attached directly to one terminal of an electrometer of the form which I have already described to you, while the other terminal of that electrometer was connected with a slide and a set of resistance coils, from which any desired fraction could be obtained of the maximum potential, which the battery C_1 Z_1 could produce. These resistance coils were accurately constructed and fitted with slides, in the manner which I have already

explained to you, so that the potential, with which the battery C_1 Z_1 was made to charge one terminal of the electrometer, could be regulated to $\frac{1}{10000}$ part of the whole, by means of the slides Nos. 1 and 2. To make an observation, these slides were moved till the potential, produced in the electrometer at X by the battery C_1 Z_1, exactly balanced that of the cable S, in connection with the other terminal of the electrometer, under which circumstances the spot of light, reflected by this latter instrument, would stand precisely at zero. This gave the means of ascertaining, with very great accuracy, the potential with which the extremity S of the cable was charged by the battery in the ship, this being measured, with an accuracy of one part in 10,000, in terms of the potential which the battery C_1 Z_1 was capable of producing. In order to eliminate the source of error which would necessarily exist, in consequence of alterations in the current produced by the battery C_1 Z_1 (and batteries can never be relied on to produce a constant or unvarying current for any length of time), a set of resistance coils, (marked No. 2), and a galvanometer, G_3, Fig. 18, were used. The galvanometer G_3 was supposed to remain constant in its indications during the whole time the cable was being laid; this object was, for all practical purposes, attained; when therefore the current of the battery C_1 Z_1 was passed through it, the resistance of the coils No. 2 could be so adjusted, as to obtain a perfectly constant deflection upon it: the means were thus given of directly regulating the current of the battery C_1 Z_1 and it was known to a certainty that the difference of potential, produced by it between the extreme terminals of the large set of resistance coils, was uniform: that is to say that the reading of 3,500, as shown on the diagram for one day, was exactly equivalent to a reading of 3,500 for any previous day.

You will perceive that the utmost care was taken to ascertain the exact potential of the extremity S of the cable, not only as a test of its insulation but in order that, in the event of a fault or injury to the cable occurring, reliable data might be at hand which, in combination with the observations taken on board the ship, would afford the means of calculating the position of that fault with very considerable accuracy.

Tests on board ship.

It was desirable that the tests on board the ship should be less complicated than those on shore, and they were consequently arranged in the more simple form shown in diagram Fig. 19. They consisted of a simple Wheatstone's bridge, in connection with battery No. 1, one pole of which was connected with the point Z from which, the plug P being out while the plugs P_1 and P_2 were in, the current would be divided and pass, a part by the resistance coils No. 1, to the point W, and a part through the right hand section of the slide and coils to the point X, forming two sides of the bridge, the other two being represented by the resistance of the insulating sheath of the cable and the left hand section of the slides. When the plugs P_1 and P_2 were in, there was also a circuit from W to X, through the galvanometer G, completing the combination. Now the shore extremity of the cable being always insulated, the means of determining the insulation of the cable itself

Wheatstone's Bridge.

were very simple : the galvanometer G would of course indicate when the resistances in the four sides of the Wheatstone's bridge were balanced, under which circumstances they would form a simple proportion of which three of the factors, viz., the resistance in the coils No. 1 and the right and left sections of the slide, were known and from which the fourth, the resistance of the insulation of the cable, could be found.

The resistance of the coils No. 1 was not altered, but the galvanometer G was brought to rest by the adjustment of the moveable part of the slides. If any injury, causing a leak, had occurred in the cable, the Wheatstone's bridge would have been used in determining the position of that leak, by simply balancing the resistance as already described, when the difference of resistance in the cable thus determined would, in conjunction with the observation at the shore end, have given the required data for calculating the position of such leak with considerable accuracy.

Direct insulation alternative test.

If anything had gone wrong with the Wheatstone's bridge, there would have been still the means of applying the direct insulation test, by simply removing the plugs P_1 and P_2 and inserting the plug P, when the current, escaping through any leak, would have been at once indicated on the galvanometer G the deflection of which would, under such circumstances, be largely increased.

Regulation of potential of battery.

The resistance coils No. 2 were arranged, in connection with the galvanometer G_1, to regulate the potential of the battery No. 1, in the same manner as I explained to you the resistance coils No. 2 and galvanometer G_3 (Fig 18), were used for regulating the potential of the battery C_1 Z_1. Battery No, 2 (Fig 19) was used, as I have already described, in connection with the inverting keys attached thereto, for speaking to the shore.

Galvanometer made as sensitive as possible when testing insulation, and less sensitive when used in transmitting signals.

It was necessary to render the galvanometer G, (Fig 19), extremely sensitive when the insulation test was made, in order to ensure as fine a balance as possible in ascertaining that insulation; whereas, when signals were to be received on it, its sensitiveness had to be reduced, to keep the vibrations of the spot of light within certain limits; for this purpose it was supplied with a shunt, as shown in the diagram. Between every letter, the galvanometer G was rendered very sensitive and an insulation reading taken, but practically the insulation test was never off, for had any considerable fault occurred during the process of speaking, the shore end of the cable having been always insulated and that on board ship in connection, through the galvanometer and slides, with the battery, the leakage of the current would have produced a very considerable change in the indications of the galvanometer G, a far greater change than could possibly have been produced in transmitting the signals.

You will thus perceive that, during the whole process of submergence, the shore end of the cable was always insulated and the tests, whether for signalling or any other purpose, were never removed; this continuity of the tests, was the great advance made, in the last and successful expedition, over the former ones. Luckily no fault occurred,

and no alteration was necessary in any of the preconcerted arrangements in connection with this great undertaking.

I have now explained to you, as fully as time will permit, the nature, application, and use of the several tests employed in carrying out the greatest, most important, and most successful of submarine telegraphic operations, one also for which many of the instruments which I have had the pleasure of showing were specially devised, viz., the submergence of the Atlantic Cable of 1866.